S. HRG. 100-385

IMPLICATIONS OF THE FINDINGS OF THE EXPEDITION TO INVESTIGATE THE OZONE HOLE OVER THE ANTARCTIC

JOINT HEARING

BEFORE THE

SUBCOMMITTEES ON ENVIRONMENTAL PROTECTION

AND

HAZARDOUS WASTES AND TOXIC SUBSTANCES

OF THE

COMMITTEE ON
ENVIRONMENT AND PUBLIC WORKS
UNITED STATES SENATE

ONE HUNDREDTH CONGRESS

FIRST SESSION

OCTOBER 27, 1987

Printed for the use of the Committee on Environment and Public Works

U.S. GOVERNMENT PRINTING OFFICE
80-438 WASHINGTON : 1988

For sale by the Superintendent of Documents, Congressional Sales Office
U.S. Government Printing Office, Washington, DC 20402

5321-15

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IMPLICATIONS OF THE FINDINGS OF THE EXPEDITION TO INVESTIGATE THE OZONE HOLE OVER THE ANTARCTIC

TUESDAY, OCTOBER 27, 1987

U.S. SENATE,
COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS,
SUBCOMMITTEES ON ENVIRONMENTAL PROTECTION,
AND HAZARDOUS WASTES AND TOXIC SUBSTANCES,
Washington, DC.

The subcommittees met, pursuant to notice, at 10 a.m., in room SD-406, Dirksen Senate Office Building, Hon. Max Baucus (chairman of the Subcommittee on Hazardous Waste and Toxic Substances) presiding.

Present: Senators Baucus, Lautenberg, Reid, Graham, Chafee, Warner, Stafford, and Pressler.

OPENING STATEMENT OF HON. MAX BAUCUS, U.S. SENATOR FROM THE STATE OF MONTANA

Senator BAUCUS. The subcommittee will come to order.

Ladies and gentlemen, let me welcome you to today's hearing on the recent scientific expedition to Antarctica. This is a joint hearing of the Hazardous Wastes and Toxic Substances Subcommittee and the Environmental Protection Subcommittee. The second subcommittee is chaired by Senator George Mitchell from Maine. He is presently attending the Iran/Contra Committee meeting, trying to decide what subsequent actions they should take, so it is unlikely that he will be here for today's hearing, although he may be able to join us for part of today's hearing.

Last May, this subcommittee heard three days of testimony on the problem of stratospheric ozone depletion. Two critical questions were then raised. First, what do we know about the cause of ozone depletion; and, second, to the degree that we understand it, what do we do to prevent it, that is, the depletion.

Since then, two significant events have occurred. One is scientific, and the other political.

First, the scientific. In August, the talents of over 150 scientists, engineers, and support personnel from across the globe were martialed for a major investigation of ozone depletion in Antarctica.

While this extraordinary scientific effort was going on, diligently collecting and analyzing data, the second event occurred. Forty-five nations agreed to work together to significantly reduce the use of chlorofluorocarbons worldwide over the next decade.

That 45 countries could agree on an enforceable agreement to protect the world's environment is a monumental step for our world. Yet, the magnitude and gravity of ozone depletion is still critical. Certain questions still arise.

Should the rate of CFC reductions be increased?

Does the current agreement go far enough toward reducing CFC emissions?

Already new scientific evidence seems to point toward the need for an even more vigorous effort to protect upper atmosphere ozone.

Today's hearing will address these questions. The science of ozone depletion is becoming more robust. The recent expedition to Antarctica made a significant step forward in understanding the role of man-made chlorofluorocarbons and destroying stratospheric ozone.

Specifically, the expedition confirmed that man-made chemicals are primary source, of the problem. Yet, the questions still remains:

What does this ozone hole really mean for the rest of the world; and what, if anything, can we do about it?

Even if the hole exists only over Antarctica, are the levels of ozone depletion large enough to disrupt the biology of the surrounding oceans, or adversely affect worldwide ozone levels?

Will the level of ozone depletion ever stabilize, or will it continue to grow?

These questions assume a hole that exists only over the Antarctic, but what about the possibility of holes or reductions developing over other parts of the globe?

The National Science Foundation is already in the early stages of planning a trip to the Arctic to look for an ozone hole there this next spring.

As we continue to seek answers to these and other questions, it is evident that the present worldwide policy of reducing CFC emissions be maintained, and also probably that policy should be strengthened and built upon.

The Montreal Protocol must be agreed to before 1990. The United States, as both a major producer and consumer of ozone depleting substances, must continue to take the lead in this area, and we must ask whether the Montreal Protocol is broad enough to sufficiently address the problem. We have a framework for international cooperation to protect the world's atmosphere so it is important that we not stop there.

I plan to push toward fulfillment of the Vienna Convention, both here in the United States and abroad. Testimony provided today will help us know how far and how quickly we need to move in limiting the use of ozone depleting substances.

I might also add that while today's hearing is focusing on stratospheric ozone depletion, CFCs are also a major greenhouse gas. The Montreal Protocol can provide a framework to address the tougher problem of controlling global warming.

Senator Chafee, Senator Mitchell, Senator Stafford, and I have been working on a resolution calling upon the United States and all nations of the world to prepare for negotiations to control greenhouse gases by June 1989 when the UNEP governing council is scheduled to meet.

Before we continue, I would like to recognize our guests from the Soviet Union who are here at today's hearing. Dr. Kazakov, Dr. Karol, Dr. Meletsov, Dr. Binikov, Dr. Bidiko, and Dr. Lavonoff are all here today. They are members of the U.S./USSR Bilateral Agreement on the Protection of the Environment. They are with Working Group No. 8, which is concerned with climate change, and also concerning stratospheric ozone depletion.

I wonder if all of you, gentlemen, could please stand so that we can all recognize you.

[Applause.]

Senator BAUCUS. We are very happy that you are here, gentlemen. We also very much hope that you make the most of your time here in our country. If there is any way that we, here in the Congress, can help you, I know that I and Senator Chafee, and others, would make ourselves available to you if you have some specific questions you may wish to ask of us, or some specific points you want to make to us. You have the full whole-hearted cooperation of all of us on this subcommittee and also the full committee in working toward the environmental atmospheric solutions to these problems. I want to thank you again for being here.

I notice that Senator Chafee is here. Senator, do you have a statement?

OPENING STATEMENT OF HON. JOHN H. CHAFEE, U.S. SENATOR FROM THE STATE OF RHODE ISLAND

Senator CHAFEE. Thank you very much, Mr. Chairman.

First, I want to thank you for holding these hearings. They are very, very interesting. Both of us have matters on the floor that we are involved with right now. They are bringing up the catastrophic health bill and, particularly, the prescription drug matter that I have been deeply involved with. But I didn't want to miss this presentation this morning. So I want to commend you for having these hearings.

I also want to join in the welcome to the guests from the Soviet Union. It is my privilege to have met with some of these folks previously, and I hope that we all can work cooperatively on these challenges presented by the depletion of ozone layer.

For some time, quite a number of us have been working on the related problems of the ozone depletion, the greenhouse effect, and the global climate change. The ozone issue, which is the subject of today's hearing, has been receiving a good deal of attention, as we know. First, there was the Montreal Agreement, then, in early October, there was more news from Antarctica, the subject of today's hearing.

Although ozone is in the news, we can't afford, it seems to me, to forget the problems of the greenhouse effect and global climate change, both of those. The change in climate is extremely important.

Mr. Chairman, I would put the balance of my statement in the record, and I hope that this will encourage others to do likewise, sending a good example.

Senator **Baucus**. Thank you, Senator. I appreciate that.

[Senator Chafee's written statement follows:]

OPENING STATEMENT OF HON. JOHN H. CHAFEE, U.S. SENATOR FROM THE STATE OF RHODE ISLAND

For quite some time, a number of us have been working on the related problems of ozone depletion, the greenhouse effect and global climate change. The ozone issue, the subject of today's hearing, has recently been receiving a great deal of attention. First there was the Montreal agreement in mid-September, a remarkable achievement and a significant first step in our effort to protect the ozone layer. Then, in early October, there was more news from Antarctica—the subject of today's hearing.

Although "ozone" is in the news, we cannot afford to forget the problems of the greenhouse effect and global climate change. The international process that led to the Montreal agreement can and should serve as a model for dealing with these matters.

Picking up on the positive aspects of the ozone negotiations, and recognizing that several years of cooperative, international work negotiations preceded the Montreal agreement, several of us are writing and preparing to introduce in the Senate, a Resolution calling for an international convention on the global climate change issue.

This convention should establish the framework for an agreement to control greenhouse gases much like the Vienna Convention to Protect the Ozone Layer and the Montreal agreement to control ozone depleting chemicals.

Turning to today's hearing, it should be noted that the ozone agreements are good models only if they are effective agreements. In the sessions leading up to Montreal, all of the parties understood that the Antarctic "hole" was not the basis for the agreement. In fact, Dr. Tolba, the Executive Director or the U.N. Environment Program, a prime mover behind the agreement, made an explicit pledge to call an emergency session to reopen the agreement if it turns out that the "hole" is caused by CFCs.

The most recent findings from Antarctica are very disturbing. Even though they are preliminary and are not 100% conclusive, they raise some serious questions about the Montreal agreement. It is true that we cannot say for certain that the "hole" has global implications—although common sense tells us it must. Nevertheless, if for no other reason than to protect the Antarctic ecosystem, we should be moving to eliminate—not just reduce—CFCs, and all other man-made sources of chlorine, as quickly as possible.

Our scientific understanding of this phenomenon is advancing at an incredible rate. Given what we know today, it seems to me that we should be doing at least two things: first, the U.S. and all other countries should ratify the Montreal agreement as quickly as possible; and second, an emergency session of the parties should be called to review the most recent data. The meeting scheduled for 1990 is simply too far away.

I look forward to hearing from today's panel of experts and look forward to continuing to work with you Mr. Chairman.

Senator **Chafee**. I hope they all heard that.

Senator **Baucus**. We will soon find out.

Senator Lautenberg.

Senator **Lautenberg**. Thank you, Mr. Chairman. I have no statement, just to commend you for holding these hearings. All of us are concerned about the changes in the atmosphere, particularly with ozone. I commend you for bringing together an illustrious panel.

I also want to extend my welcome to our visitors from the Soviet Union. It is this kind of cooperation, I think, that can melt down a lot of differences when we work on areas of common interest, and I am pleased to see them here.

Thank you, Mr. Chairman.

Senator **Baucus**. Thank you very much, Senator.

Senator Reid.

OPENING STATEMENT OF HON. HARRY REID, U.S. SENATOR FROM THE STATE OF NEVADA

Senator REID. Mr. Chairman, I would ask that my statement be made part of the record.

Senator BAUCUS. Without objection.

Senator REID. I appreciate you and Senator Mitchell holding these hearings. Like Senator Chafee, we all have to much to do today, but in spite of the shortness of time, I look forward to listening the witnesses.

[Senator Reid's statement follows:]

OPENING STATEMENT OF HON. HARRY REID, U.S. SENATOR FROM THE STATE OF NEVADA

Mr. Chairman, the subject of our hearing today is disturbing because of the implications it holds for present and future inhabitants of this country and the world. The reported rapid depletion of the earth's ozone layer over Antarctica appears to suggest that those wonderful, supposedly inert chlorofluorocarbons, of yesterday are today's ticking time bomb for the earth's environment. Even though few of us here today will directly experience the effects of a reduction in ozone over Antarctica, the continued depletion of the ozone layer over the whole earth may eventually be felt by us all. The increased transmission of ultraviolet light through a thinned ozone layer could result in serious consequences for human health and the environment that sustains us.

While it is important to continue to gather more data on the problem, the preliminary data reported to date indicates that strong actions are needed today. The treaty signed in Montreal, Canada on September 16, 1987 must be ratified and implemented soon. While we wait for this to occur, emissions of chlorofluorocarbons will continue and levels of these chemicals in the atmosphere will continue to grow. We cannot afford to use the earth's atmosphere as a test chamber to study the effects of chlorofluorocarbons on ozone while we wait for the final results of the studies to be published.

Mr Chairman, I commend you and my colleagues for the interest that you have shown in this issue. I share this interest and believe that this hearing will further heighten the awareness that many people have in man's apparent ability to deplete the earth's ozone layer and warm the earth. The scientists who testify before us today may be able to tell us to what extent we are modifying our environment and how much time we have to act to protect it before our time runs out. I trust that this Congress and the American people will have the resolve and time to change our use of these chlorofluorocarbons before the earth's ozone layer runs out.

Senator BAUCUS. Senator Graham.

OPENING STATEMENT OF HON. BOB GRAHAM, U.S. SENATOR FROM THE STATE OF FLORIDA

Senator GRAHAM. Mr. Chairman, I also appreciate your and Senator Mitchell's leadership on this issue. I have an opening statement, which I would like to submit for the record.

I am pleased that we are joined by our friends from the Soviet Union, which indicates the international dimensions of our commitment to this, and the opportunities, which the preservation of our planet provides for international cooperation, which might lead to truly fundamental steps in the preservation of our planet.

[Senator Graham's statement follows:]

OPENING STATEMENT OF HON. BOB GRAHAM, U.S. SENATOR FROM THE STATE OF FLORIDA

Mr. Chairmen—Senator Mitchell and Senator Baucus—I commend you both for bringing these witnesses together today to relay findings and implications in regard to the Antarctic expedition. As we will hear today, several theories exist as to the cause or causes of stratospheric ozone depletion. I am hopeful that data gathered on and pursuant to the expedition will shed some light on these theories and allow us to pin down the true nature of the depletion that is being experienced. Such definitive findings will allow us to respond appropriately in reducing or eliminating the causes.

I thank you both for your interest in this phenomenon. I look forward to learning from our witnesses today, as another step toward solving the mystery and mitigating this depletion.

Senator BAUCUS. There is another representative of the Soviet Delegation who is not yet here this morning; we hope that he will be able to join us later, and that is Dr. Bidiko. Dr. Bidiko is one of the first scientists in the world who raised concerns about global climate change, as I understand it. We hope that Dr. Bidiko will be able to join us a little later on this morning.

Our witnesses at today's hearing are, first, Dr. Peter Wilkniss, with the National Science Foundation in Washington, D.C.; second, we will hear from Dr. Robert T. Watson from the National Aeronautics and Space Administration; third, Dr. James G. Anderson of Harvard University; fourth, Dr. Mack McFarland with DuPont, representing the Fluorocarbons Program Panel of the Chemical Manufacturers Association; fifth, Dr. Michael B. McElroy from Harvard University; sixth, Dr. F. Sherwood Rowland from the University of California at Irvine; and seventh, Dr. Michael Oppenheimer of the Environmental Defense Fund in New York City. First, we will hear from Dr. Wilkniss.

Gentlemen, I would like each of you to summarize your testimony in about five minutes. We will not, on this panel, ask any questions of the panelists until each of you has testified. It is our hope that we can get a discussion going here, a little dialogue, and maybe get a little better idea of where the truth, therefore, lies.

Dr. Wilkniss, why don't you begin?

STATEMENT OF DR. PETER WILKNISS, NATIONAL SCIENCE FOUNDATION

Dr. WILKNISS. Good morning, Mr. Chairman. I appreciate the opportunity to testify before this committee. According to your direction, I will summarize and submit a complete statement for the record, with your permission.

Senator BAUCUS. Without objection, all statements will be included in the record, so you don't have to go through all that. Go ahead.

Dr. WILKNISS. In the North and South Polar regions, interactions between the vast ice sheets, the oceans and the atmosphere represent driving forces as well as indicators of global change. For instance, the ice sheets preserve input from natural sources such as volcanic dust layers and meteorites, and also manmade input, the so-called "greenhouse gases," for example, carbon dioxide and methane. So the ice sheets afford a view of the past and possibility to project into the future.

Modern science, lately, has acquired the means to look at ongoing changes, for example, the climatic warming trends that are documented in the Arctic permafrost and, of course, the issue at hand, the depletion each spring of the Antarctic ozone layer.

Through the United States Antarctic Program, modern scientific research has been, in all disciplines, carried out on the Antarctic

Continent since the International Geophysical Year preparation in 1956. It is important to note that the longstanding support by the Congress provided the means to create the scientific expertise and the logistics capability to launch the National Ozone Expedition No. I in August of 1986, shortly after the ozone hole depletion was reported by the British Antarctic Survey research of Dr. Farman.

The National Ozone Expedition No. II results were obtained between August and October of this year. They have just become available. They agree and improve on NOZE-I results and corroborate further the recent NASA aircraft measurements on unusual chlorine chemistry in the Antarctic atmosphere.

Furthermore, at McMurdo, Antarctica, the measurements show the lowest ozone levels yet, a more extensive vertical depletion of ozone, and a structure in the ozone hole with 97 percent depletion in a layer up to four kilometers thick at an altitude of 15 kilometers.

Later measurements carried out at McMurdo identified polar stratospheric clouds at altitudes from 10 to 22 kilometers, coinciding with the ozone depletion, with significant changes in the vertical distribution occurring in time intervals as short as five minutes.

The implications of this research for the Antarctic Program—First of all, we have to obtain assured year-round access. We have not been able to make critical measurements at the time when the ozone hole first appears in Antarctica in mid-winter, July and August.

Secondly, we are scrambling to provide the housing for the very complicated equipment. In other words, the ozone research has led to almost a quantum jump of the sophisticated, scientific experiments that we are conducting on that continent.

Thirdly, we are installing very enhanced systems to use the orbiting weather satellites and communication satellites to provide additional support to study the dynamics of the Antarctic atmosphere and, at the same time, to improve our weather forecasting, which is important for year-round access.

Finally, we are looking at a different management of the year-round polar science on the continent through research support centers.

Let me turn to the long-term impact. Everybody wants to know about the biomass.

Through the NOZE-II expeditions, we have funded two studies. The first one will concern itself with the impact of enhanced UV radiation on the marine phytoplankton, the first member of the food chain in the Antarctic waters; and, secondly, we have a experiment concerned with the ability of the Antactic organisms to repair UV induced damage in the DNA—the DNA, of course, being the carrier of the genetic code—and if there were any impact that would lead to mutations.

Finally, when the ozone hole got worse beyond all expectations, we became concerned about the health and safety of our people in Antarctica. Antarctic expeditioners are the first ones, those of the U.S. and other nations, to experience an impact. We have no experimental evidence, UV measurements, as to the levels that occur. So we had to resort to preliminary calculations of what levels to expect.

If we take the worst conditions, and I want to underline, worst conditions, of a combination that we have not seen yet in Antarctica, to say it in understandable terms, a person would experience about four times the UV radiation that you would get in the summer, in Miami, at the beach.

So far, these worst conditions haven't come together, but we are in the process of instituting monitoring systems and to look at protective measures, and the first things that will be affected are the eyes of the people in the Antarctic.

Finally, we believe that we have to maintain a vigorous program in all disciplines to follow up on the effects of the ozone hole, but also to detect any other effects. That can only be done on an international basis, the continent being so large.

The first example that I would like to mention is the tip of South America where any expansion of the ozone hole will be first felt by the plants, animals, and people. We are now talking with our colleagues in Argentina and Chile to provide for joint, long-term, ecological monitoring experiments.

Thank you, Mr. Chairman.

Senator **Baucus**. Thank you, Dr. Wilkniss.

Next, Dr. Robert Watson, who has been very heavily involved in this project. Dr. Watson.

STATEMENT OF DR. ROBERT T. WATSON, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Dr. **Watson**. Thank you, Mr. Chairman and members of the subcommittee.

My report will be a report of the provisional findings from the scientists themselves from Punta Arenas. I will mainly stress the non-chemical aspects of the results so that Dr. Jim Anderson can focus on evidence of perturbed chlorine chemistry and the impact of the chlorine on the ozone layer.

I would first like to note that this particular project would not have been successful without strong cooperation from NSF, NOAA, CMA, and very strong international cooperation with the government of Chile, and the British Meteorological Service in the United Kingdom.

The first question that we need to ask is how low is ozone in 1987? I would like, with your indulgence, to show you a few viewgraphs.

Figure 1 is TOMS satellite data for ozone on August the 17th. The figure shows that ozone south of 60 degrees ranged between 225 and 275 Dobson Units.

Senator **Chafee**. Wait a minute. Don't go too fast. What do we have in this chart?

Dr. **Watson**. Figure 1 is a polar stereographic projection of the earth. The South Pole is located in the middle of the figure. This is the Antarctic Continent here. You can see South America is around here. The figure is a color map of how much ozone is in the earth's atmosphere in the southern hemisphere.

Senator **Reid**. What is at the bottom of the chart?

Dr. Watson. It just shows the South Pole, and the color code for the NIMBUS-7 satellite total ozone data. Normally, over Antarctica, at this time of year, the abundance of ozone ranges from 250 to 275 Dobson Units.

Senator Chafee. That is a measurement unit of ozone.

Dr. Watson. Correct. That is how much ozone is in the earth's atmosphere. To put it in perspective, these levels would have been typical of the amount of ozone one would have seen back in the mid-1970s. I am going to show you three more days (figure 1) as we move from August through October. You will see rapid changes in the amount of ozone over the Antarctic Continent.

In mid-August, we observed 275 Dobson Units. By September the 27th, the ozone abundance has dropped down to between 125 and 150 Dobson Units. Most of the Antarctic Continent now has less than 200 Dobson Units of ozone above it. Therefore ozone decreased from 275 DU to under 150 Dobson Units.

By October the 5th, most of the Antarctic Continent had less than 150 Dobson Units of ozone, and there were even regions, over the Polar region, of less than 125 Dobson Units, a major change, nearly a 50 percent change in ozone in a one-month period. By October the 15th, the picture is similar.

Clearly one can see that there has been a dramatic change in ozone from the middle of August to the middle of October.

Senator Chafee. Slow down one minute, if you would, please.

These were taken 10 days ago?

Dr. Watson. Yes, correct. This is a satellite image, from the NASA NIMBUS-7 satellite. This type of data was available within 24 hours of each day down in Punta Arenas, Chile. The data is being collected in real time. If you wanted, we could have yesterday's ozone data ready for you by tomorrow.

We arranged that all of this satellite data was available in real time to all of the scientists in Punta Arenas for mission planning. We could then direct the aircraft to the areas of particularly low ozone.

Senator Chafee. You said that these were satellites.

Dr. Watson. This is a satellite observation.

Senator Chafee. In the previous testimony by Dr. Wilkniss, the concern was trying to operate the equipment in the middle of the winter.

Dr. Watson. Right.

Senator Chafee. In July and August. Can you get much of that data from satellites?

Dr. Watson. No. All that the satellite instrumentation will give you is the total amount of ozone. It will not give you the other parameters we need like temperature and the chemical composition of the Antarctic atmosphere.

In addition, this particular satellite will only look in the sunlit portion of the atmosphere.

Senator Stafford. Doctor, before you take that off, if you don't mind.

Dr. Watson. I was only going to point out from figure 1 that this area near the South Pole has no data in the middle of August. The reason is that it is still the polar night and the satellite needs the presence of sunlight to measure ozone.

So the discussion that Dr. Wilkniss had with you is a completely correct one. We really need to be able to study the Antarctic environment not only in the late August-September-October time frame, but even during the Polar night.

Senator STAFFORD. Doctor, on the one you have up now—this is where I need clarification—to show 400 to 450 parts per million off to the left of Antarctica there?

Dr. WATSON. That is correct. It is a region of very high ozone.

Senator STAFFORD. There is a lot of ozone, or a lot of CFCs in that area there, or is that ozone?

Dr. WATSON. We will discuss the cause of the ozone hole which is mainly centered south of 60 degrees. There has always been a region of very high ozone there, and that still persists.

There is evidence, though, that even that region of high ozone has decreased in magnitude over the last six or seven years. I will show you another figure in a minute or two that will address that.

Senator STAFFORD. All right.

Dr. WATSON. The ozone didn't change, however, monotonically, i.e., smoothly with time. There is evidence that both complex meteorology and chemistry are causing the ozone hole.

Figure 2 shows that on September the 4th, south of 60 degrees the abundance of ozone is about 275 Dobson units. Then, suddenly, within 24 hours, on September the 5th, there was more than a 10 percent drop in ozone over a fairly large region of the Palmer peninsular that then moved over the Weddell Sea on September the 6th. This is an area of three million square kilometers. A significant proportion of the area of the United States.

This, we believe, is evidence that in that particular case, it was not a destruction of ozone but a change in ozone mainly due to meteorology. It is hard to envisage more than a 10 to 15 percent change in ozone in 24 hours purely due to chemistry. So that is the evidence that meteorology, i.e. dynamics, is at least playing some role.

The next two viewgraphs (figures 3 and 4) show how low ozone is in 1987 compared to previous years. Figure 3 shows ozone at 70 degrees south. The bottom blue line is 1987. The previous lowest year was 1985, the red line. You can see, even from 1985 to 1987 a very significant change in ozone. In fact, back in 1979, the levels are significant. Ozone has fallen very substantially in the last seven or eight years.

Figure 4 shows the ozone data at 80 degrees south. Since 1979 there has been more than a 100-Dobson unit change. These are very large changes in ozone, and this particular year is the lowest ever.

I think that the next viewgraphs will completely support what Dr. Wilkniss said about the findings at McMurdo. Figure 5 shows profile ozone data from the British Antarctic Survey at Halley Bay for August the 15th, and October the 13th. The figure clearly shows the ozone concentration to decrease by more than a 95 percent—around 15 kilometers during the two months.

The conclusion is also supported by data from the Palmer Station which is also a National Science Foundation Station. Figure 6 shows the vertical profile of ozone just three days apart in October. October 6 is when the Palmer Station was outside the so-called "vortex." While October 9 is when it was inside the vortex. In the three-day period, ozone around 15 kilometers changed by more than a factor of 20. In other words, in a region, over four to six kilometers in altitude, the ozone is 90 to 98 percent less than normal. The ozone abundance literally can't get any lower in this particular altitude region. It has completely been destroyed.

It is clear that the question of whether ozone is low in 1987 has been conclusively answered. The next critical question is why? The scientists from Punta Grenas believe it takes the unique meteorological conditions present in Antarctica plus chlorine chemistry. In other words, it is neither purely chemistry, nor it is purely dynamics. There is very strong evidence that the chemistry is highly perturbed, completely consistent with what was found by the National Science Foundation last year at McMurdo.

We found large concentrations of active chlorine; very low concentrations of oxides of nitrogen, and the presence of Polar Stratospheric Clouds. We believe that the special meteorological conditions cause these very cold conditions, which results in the stratosphere being dehydrated. In addition the stratosphere is denitrified. The dehydration and denitrification are part of the reason for the ozone hole.

If we turn the question around: Would the hole be as deep if there were no chlorine in the atmosphere? The answer is, no. Chlorine is certainly a contributing cause, a major contributing cause to the ozone hole in Antarctica. Jim Anderson will discuss this in great detail so I won't dwell upon it.

We made a lot of other measurements with the two aircraft.

Senator CHAFEE. You measured the chlorine up there?

Dr. WATSON. Dr. Jim Anderson measured both the ClO free radical, which is thought to be the dominant free radical in the chlorine mechanism believed to destroy ozone, and the BrO free radical, which has also been hypothesized to cause ozone destruction. In other words, key measurements of bromine compounds and chlorine compounds were made. Dr. Jim Anderson will talk about these measurements in detail, so I won't belabor them here.

We did measure the long lived gases, fluorocarbons, nitrous oxide, and methane. At this moment, there is no evidence for what we call a general upwelling over the Antarctic, which is one of the dynamical theories that was proposed by someone who testified before you last year, Dr. K. K. Tung. We find no evidence to support his theory of sustained large scale upwelling, which is purely a change in meteorology.

The conclusion we come to is that a combination of meteorology and chemistry has caused the ozone hole in Antarctica. One of the key questions is: Could the same mechanism that is destroying ozone, to such a large extent in Antarctica, occur at other latitudes.

At this moment, our provisional analysis does not allow us to make a strong statement in either direction. We need to carefully look at our data, and we would hope to have carefully analyzed it within the next six months. There is certainly the presence of other aerosols at all latitudes. It is the so-called "yunge layer," where sulfuric acid particles exist between about 15 and 22 kilometers at all latitudes.

The question is: If the Polar stratospheric clouds in Antarctica are allowing the chlorine to be very efficient, would the yunge layer at other latitudes also allow chlorine to be much more efficient than we previously thought.

We need to look very carefully at our data. We need also to do more laboratory studies, and we need to analyze some other atmospheric composition data that scientists, auch as Dr. Jim Anderson, measured on the way to Punta Arenas.

We measured the chemical composition and particles at latitudes all the way from California to Chile. We need to look at that data very carefully to see if there is any evidence of enhanced levels of chlorine, active chlorine, ClO, at these other latitudes. That work will take at least several months before we can report back on it.

Just to summarize, we believe there is evidence that there can be short-term fluctuations in ozone, such as the Weddle Sea event on September the 4th and 5th, which are probably primarily meteorological. However, the weight of evidence strongly suggests that the main cause for the destruction of ozone over Antarctica is due to chlorine, the presence of fluorocarbons breaking down to ClO.

The crucial question is: Will there be global ramifications? Could these unique special meteorological conditions allow chlorine to be efficient at other latitudes. That is where we need more work to be done.

Thank you.

Senator BAUCUS. Thank you, Dr. Watson.

Next we will hear from the person that you previewed, Dr. James Anderson.

STATEMENT OF DR. JAMES G. ANDERSON, HARVARD UNIVERSITY

Dr. ANDERSON. Mr. Chairman, I am Jim Anderson; one of numerous principal investigators on the airborne Antarctic ozone experiment that was recently completed. Our task was to build the instrument to define the spatial and temporal distribution of the ClO free radical.

The instrument also detected BrO as part of a complement of instruments to measure the oxides of nitrogen, water vapor, condensation nuclei, aerosols, and a number of other constituents to track both the chemical and dynamical aspects of this problem.

To highlight the results of this mission in a few moments requires rather dramatic distillation. There are critical issues involving the scientific foundation of the problem, the global implications, and action required based on our findings.

In order to make progress, I will concentrate primarily on the scientific case, that is, the issue of chlorine and ozone within the Antarctic vortex. Therefore, my testimony will have a chemical flavor to it, perhaps a chemical odor as well.

I would like to first mention that progress in science is made when we adequately isolate cause and effect. This is, of course, why laboratories are built, to isolate the crucial question from dilution and confusion regarding other variables.

This morning, the Antarctic ozone question centers on a fairly simple question: Are chlorine compounds and, therefore, CFCs responsible for the destruction of ozone in the Antarctic vortex?

Two points are critical here. Fortunately, they appear virtually daily in the nation's newspapers. First, if chlorine does destroy ozone, then it does so through catalytic cycles, that is, it is a chaperone accelerating the conversion of ozone to molecular oxygen.

If these catalytic cycles take place, then they are rate limited by a single entity that couples the surface release of fluorocarbons to the destruction of ozone in the stratosphere, namely, the ClO free radical, and thereby has this molecular entity achieved the status of a household word.

Why was the recent Airborne Antarctic Expedition unique? It was unique because it asked and in large measure answered two questions which have thus far been beyond our grasp.

The first one is: Can the dynamical and chemical processes be separated inside the vortex itself, that is, can we define the chemical containment vessel that maintains its integrity from the end of Polar winter through the period required for ozone to be significantly reduced?

Second: Within this chemical containment vessel is the ClO radical of sufficient concentration to explain the removal of ozone, that is, at the proper rate.

So this sets the stage. If the answer to both questions is yes, then we have ozone surviving through the Polar night unperturbed, ClO growing dramatically as sunlight strikes the region at the end of winter, reaching a concentration adequate to describe the removal of ozone in two to three weeks. Finally, we are left with ozone eroded significantly within this chemical containment vessel containing high concentration of ClO.

What did we find?

First, let me review the geometry of the problem with an overhead very similar to that of Dr. Watson's, in which the southern tip of South America occupies the upper-region, and the ozone-hole, in this case taken on the 24th of September, extends over virtually the entire Antarctic Continent.

What we found was, primarily from the high altitude aircraft, that in fact a chemical containment vessel was present through the entire period of the mission, from the middle of August to the end of September.

Here I show a foil on August 23d defining, on the vertical axis, the concentration of ClO observed by the aircraft as it flew south, from the tip of South America into the Antarctic region. The blue line is the concentration of the ClO free radical.

The detection threshold of the instrument is adequate such that the measurements that you see on the far left are easily observable, and they are typical concentrations that we would see over our head in Washington, D.C.

As we pass through the wall of this chemical containment vessel, the ClO concentration increases by well over an order of magnitude within a few horizontal kilometers, reaching concentrations, in this case, 250 times the normal concentration.

Now, just seven days prior to that, the shape, the morphology of this containment vessel looked the same, but the black dots here at significantly lower concentration indicated the ClO distribution that we saw. Note that the above concentration has survived the

Polar winter. It remains unaffected inside and outside that chemical containment vessel.

Three weeks later, the same distribution, the same flight profile for ClO and ozone showed a dramatically different picture. In this case, the ClO concentration has reached nearly 400 times the concentration that we would find over our heads at mid-latitudes. There is an extremely steep gradiant still defining the chemical containment vessel, but ozone, rather than being unperturbed, has now dropped by well over a factor of two in the period between August 23d and September 16th.

Now, not only does this strong anti-correlation appear between the ClO free radical in blue and the ozone molecule in green, but it does so on a number of spatial scales. If we amplify, magnify the horizontal axis to look at the detailed structure of the ClO free radical, and simultaneously ozone obtained from this aircraft platform as it penetrates the wall of the containment vessel, we see strong anti-correlation on both the large spatial scale, that is, inside and outside the vortext, as well as in the small spatial scale going through the wall of that vortex.

As the systems transition from positive correlation in August to strong negative correlation in middle and late September, the time rate of change, the rate of disappearance of ozone matches, within the experimental uncertainty, with the local ClO concentration based on the best evidence we have for the chemical mechanism linking these two species.

I will close by saying that within this clearly confined chemical vessel, there exists a concentration of ClO that reached 500 times normal concentrations through the course of this mission. About that there is no doubt.

The cause and effect linking chlorine in the atmosphere to the destruction of ozone in the atmosphere has been established, although key issues regarding the specific mechanism remain. The clarity of the data in this case exceeded that often obtained in the laboratory.

Finally, the amount of ozone destroyed each year by this Antarctic phenomenon is potentially of considerable global significance.

Thank you.

Senator BAUCUS. Thank you very much, Dr. Anderson.

Senator STAFFORD. Could I just ask one quick question?

Senator BAUCUS. Senator Stafford.

Senator STAFFORD. Doctor, before you leave this, would it be safe to speculate that something like this is happening at the North Pole, or is this peculiar to the South Pole area?

Dr. ANDERSON. We believe at this point that the uniqueness of the Antarctic vortex lies in the very low temperatures achieved in that region. The Antarctic does not share the same temperature distribution with the Arctic. It is a very important point, and a very important point to speculate on, but we would have to go and find out the answer to that question. Speculation would be dangerous.

Senator STAFFORD. Thank you.

Senator BAUCUS. Thank you, Dr. Anderson.

Our next witness is Dr. Mack McFarland with the DuPont Company. Dr. McFarland is representing the Fluorocarbon Program Panel of the Chemical Manufacturers Association.

STATEMENT OF DR. MACK McFARLAND, ON BEHALF OF THE FLUOROCARBON PROGRAM PANEL, CHEMICAL MANUFACTURERS ASSOCIATION

Dr. **McFarland**. I am Mack McFarland, an atmospheric scientist representing the Fluorocarbon Program Panel of the Chemical Manufacturers Association. The panel welcomes the opportunity to address these subcommittees of the Senate Committee on Environment and Public Works on the implications of the recent Airborne Antarctic Ozone Experiment.

I would like to discuss three main points today:

First, the preliminary findings of the expedition indicate it is unlikely that conditions can exist anywhere else on the globe which would duplicate this seasonal effect.

Second, computer modeling, based upon the recently signed Montreal Protocol, indicates that the protocol still provides a reassuring margin of safety for the protection of stratospheric ozone.

Third, the Montreal Protocol contains an effective mechanism to change the CFC control measures and to assure that stratospheric ozone is protected if new scientific evidence shows that a change is needed.

Before elaborating on the above points, I would like to acquaint you with the Fluorocarbon Program Panel. The panel has a membership of 19 companies with production facilities in 16 countries. As discussed more fully in my written statement, the CMA panel has been dedicated for over 15 years to the global coordination of and financial support for research into the atmospheric fate of chlorofluorocarbons.

To these ends, the panel has expended over $20 million toward the goal of understanding the environmental implications of the production and use of CFCs. Our joint funding of the recent Antarctic Experiment is the latest example of the panel's efforts to support advancement of the science.

The Antarctic phenomenon is highly unlikely to have global significance. The preliminary findings indicate that both unique climatic conditions, meteorology, and unusual atmospheric chemistry contribute to the recently observed seasonal ozone decreases over Antarctica. It appears that meteorology alone directly leads to some of the seasonal decrease. Thus, a hole of some proportion would probably have been formed even if man-made chlorine compounds had never been emitted into the atmosphere.

Clearly, it also appears that chemistry contributes to ozone decreases within the chemically perturbed region, but again this is possible only because of unique meteorology. At present, we cannot determine the relative contribution of meteorology and chemistry to the seasonal decreases of ozone in Antarctica.

Available information does suggest that the unique conditions in Antarctica will limit this phenomenon to the Antarctic spring time only. Even in the other most similar region of the world, the Arctic, the meteorology effectively precludes a similar situation.

With this in mind, the protocol provides a reassuring margin of safety. As you know, the initial step freezes emissions from developed countries at 1986 levels. The protocol then calls for subsequent reductions at specified levels.

Recent computer modeling studies of the impact of these steps shows that, between now and 2060, calculated future reductions of stratospheric ozone will be less than natural fluctuations that have occurred over the last 30 years. When the effect of the emission reductions of the protocol are included in the model calculations, we find that ozone concentrations remain essentially constant.

These calculations lead the CMA panel to conclude that the current protocol is sufficient to protect stratospheric ozone. A report summarizing the computer modeling results is nearing completion and I would like the chairman's permission to submit it for the record when it becomes available.

Senator **Baucus**. Without objection.

Dr. **McFarland**. The last point I would like to make is that the protocol is a living document because its signatories recognized the complexity and uncertainty of atmospheric science. The policymakers provided for period review of the science to assure environmental protection into the future. If the science indicates that the implementation strategy needs to be adjusted, a mechanism is available to do just that. As a scientist with over a decade of experience in this field, I believe such provisions are prudent.

The first review will be conducted in 1989, by which time the data from the recent Antarctic Experiment will have been assimilated and interpreted. This review process ensures continued environmental protection without unduly restricting the valuable contributions of CFCs to worker and consumer safety and to our standard of living.

In closing, on behalf of the CMA panel, I want to congratulate the participants in the Airborne Antarctic Ozone Experiment. In my 13 years of studying atmospheric ozone, I have not participated in, nor heard of, a more successful mission. The Fluorocarbon Program Panel is proud to have participated in the funding for this important effort.

I would be happy to answer any questions you may wish to ask about this matter.

Thank you.

Senator **Baucus**. Thank you very much, Dr. McFarland.

Next, we will hear from Dr. Michael McElroy of Harvard University.

STATEMENT OF DR. MICHAEL B. McELROY, HARVARD UNIVERSITY

Dr. **McElroy**. Thank you, Mr. Chairman and members of the committee. I appreciate the opportunity to speak to you today on the subject of Antarctic ozone.

Some 16 years have gone by since Harold Johnston first drew attention to the possibility that exhaust gases from supersonic aircraft could be responsible for a reduction in stratospheric ozone. Over this period, literally hundreds of papers have appeared in the scientific literature examining various aspects of the stratospheric chemistry.

A subject of research, which was somewhat isoteric, in 1971, moved to the front stage of atmospheric science, and literally to the front pages of the world's newspapers following the appearance of the paper by Molina and Rowland, and it has remained there ever since.

We have come a long way over the past 16 years in my opinion. We have developed a remarkable series of instruments, some of which the results of which you have seen here this morning. We have satellites capable of sensing changes in the atmosphere. We have laboratory experiments capable of testing theories. We have models which have become increasingly sophisticated and, in my opinion, reliable.

The question, then, is how can we account for the remarkable and complete surprise that greeted the report in "Nature," only two years ago, by Farman, Gardiner and Shanklin, announcing the large decrease in ozone appearing over Antarctica in spring?

The answer, I believe, is that the chemistry operating in the extreme environments at high latitudes is quite distinct from that of mid-latitudes, and our attention since 1971 has been directed mainly, and properly so, to the mid-latitude regime. But I think that we have now been forced to switch our emphasis to the polar region, which surely deserves great attention.

I think that in two years, we have made remarkable progress in reacting to the challenge of the new results from Antarctica. Indeed, of course, it is a subjective estimate, but I believe that we perhaps understand 80 percent of what is going on there starting from a base of essentially zero two years ago.

I think we know that the important characteristic of the high latitude stratosphere is the exceptionally cold temperature attained in late winter and early spring. We believe that these temperatures allow formation of clouds, which contain crystals of nitric acid, in addition to water. We believe that a portion or a fraction of the particles in these clouds grow large enough to fall. Literally, in the stratosphere over Antarctica, it snows nitric acid ice.

We believe that hydrogen chloride can be incorporated in the stratospheric aerosols, and we believe that reactions involving chlorine nitrate and hydrogen chloride in the particles release the precursors, which leads eventually to the exceedingly high concentrations of ClO, the chlorine oxide radical presented by my colleague, Jim Anderson.

Once the radicals appear, it is not difficult to work out the rate of loss of ozone. The chemistry, in my opinion, is reasonably well defined. The models are capable of handling the job from there, given that particular set of information from the direct observations.

I think that the results from Chile can provide a benchmark, which we can use to assess the reliability of the models. I believe that we are on the right track. There is little doubt in my mind at this stage that industrial sources of chlorine and, perhaps, bromine contribute in a major way to the loss of ozone observed in recent years in spring over Antarctica.

Let me just capsulize what I consider the key new pieces of information as announced this morning and at the press conference a few weeks ago.

Number one, the abundance of chlorine oxide was exceptionally high, more than 400 times larger inside the perturbed region than outside. That is an incredibly large change over a small spatial scale. Concentrations of chlorine oxide correlated or ante-correlated with ozone. Chlorine oxide was high, ozone was low during the disburbance, and vice versa.

The abundance of nitrogen oxides in the gas phase was very low. There was evidence of nitrate in the particulate phase. The abundance of nitrogen chloride was very low. The stratosphere was exceptionally dry.

My estimate that we have come a long way in understanding is based, in fact, on the point that these results, spectacular and very important as they are, come as no great surprise in light of the work over the past two years.

When I testified a few years ago on the subject of stratospheric ozone, I took a rather cautious approach. I believed then that the penalty involved in waiting a few years to test our understanding of the stratosphere against observation, to allow our models to evolve as new data were obtained and assimilated, was not severe. The risk implicit in a delay of a few years justified, I thought, the benefit of a more orderly and informed assessment. The changes in stratospheric ozone were expected to set in gradually.

My confident of the validity of this approach was shaken by the initial discovery of the hole over Antarctica. There remained, however, the possibility that the hole represented a natural phenomenon. The results from the NOZE Expedition last year lent further doubt to the credibility of the cautious approach.

The results from this year indicate in my mind that it is time to take a stand. There is no longer reason to doubt, in my opinion, that gases containing chlorine are responsible in large measure for the dramatic large-scale change in the stratosphere observed over Antarctica. It is difficult to remain detached when ozone is essentially eliminated from almost 10 percent of the southern hemisphere for a period as long as two months.

I believe that we passed an important threshold in 1978. The Antarctic hole is here to stay. It may fluctuate from year to year, depending on the prevailing stratospheric meteorology. When the stratosphere is cold, it will be severe. When the stratosphere is relatively warm, the hole will be present though less dramatic. It will persist for 100 years even if we effect a complete immediate ban on the release of chlorofluorocarbons. The long lifetime of chlorofluorocarbons guarantees that the hole will remain a lasting legacy to posterity.

The initiative taken by the United Nations in Montreal deserves our acclaim. It represents an important and balanced approach to the threat posed by ozone at mid-latitudes. The cooperation and support of industry in advance of the Montreal meeting was particularly laudable.

The delegates in Montreal were instructed not to consider the Antarctic phenomenon in their deliberations. I don't disagree with that decision, but the situation has now changed. The chemistry responsible for the enormous drop in ozone over Antarctica is distinct. It is quite different from the chemistry that occupied our attention in 1974. It is not a substitute, but an addition to the earlier concern. The associated impact on Antarctica sets in not slowly but precipitously.

Let me echo the comments of earlier speakers. We owe a great debt of gratitude to the the scientists and pilots who labored hard in Chile to obtain the remarkable results we heard about today. We are indebted also to the teams of scientists and support personnel who labored on the ground in Antarctica this summer and last. Without their heroic effort, we would remain, doubtless, in the dark.

Stratospheric effort is truly a team effort. There is little the individual can accomplish alone. Progress has involved an unprecedented collaboration of government and industry. The work has been truly international in scope, consistent with the challenge.

To wrap up. There is more to be done. We need to assess the implications of the chemistry observed over Antarctica for other regions of the earth.

As was asked by one of the Senators, can we expect the Antarctic phenomenon to show up in the Arctic? What implications does it carry for ozone at mid-latitudes?

We may have opinions individually on these issues, and we do, but opinion is no substitute for hard scientific fact. In the interim, we must respond to the facts in hand. There is, in my opinion, a need for immediate additional cuts in the release of industrial chlorinated and brominated hydrocarbons.

Montreal showed the way. We must continue the historic precedent set by the delegates at that meeting in September. The stakes are high. We must act, I believe, to maintain the integrity of the global environment for generations not yet born.

Thank you.

Senator BAUCUS. Thank you very much, Dr. McElroy.

The next witness will be Dr. Sherwood Rowland from the University of California at Irvine.

STATEMENT OF DR. F. SHERWOOD ROWLAND, UNIVERSITY OF CALIFORNIA AT IRVINE

Dr. ROWLAND. Coming as I am after five previous speakers, many of the things which I might have said, and which are included in my written testimony, need not be repeated here about the science that is going on over Antarctica. But I have several points that I would like to make.

The first has to do with the importance of heterogeneous reactions, that is reactions occurring on surfaces, in the Antarctic. This, in the last three years, is a new concern in atmospheric chemistry and in stratospheric chemistry. The fact that this heterogeneous chemistry is important in the Antarctic makes us be concerned about its importance in the Arctic, and in the temperate and tropical regions.

The chemistry that is going on in the Antarctic is in the laboratory almost impossible to prevent on any surface that one tries. I think that it is going to be a very risky, foolhardy thing to do, to assume that the chemistry of the Antarctic won't occur in the atmosphere over the temperate and the tropical regions.

It is clear that the Antarctic has very special meteorological conditions because, after all, you lose 50 percent of the ozone in three or four weeks. We know that that hasn't happened in other places. But we would be devastated if we had 50 percent loss of ozone in three or four weeks anywhere else.

What we have to be concerned about are losses of ozone that are much smaller than that, but carried out over an extensive period of time. Heterogeneous chemistry, it seems to me, is likely to be important in other latitudes than just in the Antarctic.

The second point I would like to make is elaborated upon in my testimony. It has to do with the measurements that have been made over the ground stations at many locations in the north temperate zone.

In my testimony, I show graphs of the behavior of ozone over three stations: Arosa in Switzerland, which has a record which goes back more than 55 years; Caribou in Maine; and Bismarck in North Dakota. In all three of those locations, if you compare the last ten years against the previous 10 years or, in the case of Arosa, the last 15 against the previous 40 years, there is a distinct loss of ozone in the wintertime at these stations.

This is not an Antarctic ozone hole. This is ozone lost over the United States and over Western Europe, and ozone loss which is especially large in the winter conditions, losses on the order of 15 to 20 Dobson Units, that is 6 or 7 percent seen in some months at those individual stations. This means that we already know that we have a concern in the temperate zone, and not just in Antarctica.

The third point that I would like to make has to do with the protocol, in a technical way, as it has been written in Montreal. The discussion of ozone depletion in the scientific community, over an extensive period of time, has been carried out technically in terms of saturated perhalo chlorofluorocarbons.

The Montreal Protocol became very specific and listed five of these chlorofluorocarbons as compounds for which controls should be enacted. These compounds are fluorocarbons 11, 12, 113, 114, and 115. They do not specify controls on some other commercially available fluorocarbons such as fluorocarbon 13, and fluorocarbon 112.

Already I have heard reports both in the United States and in Japan of companies that are pushing fluorocarbon 112 as a substitute for the fluorocarbons that are on the proscribed list.

We are not going to make much headway if we find people switching from one ozone threatening substance to another ozone threatening substance, one whose threat is approximately equal to the one that is being replaced, simply because it is not on the protocol list.

I urge the Senate to consider legislation which would expand the list of compounds that are affected to include all of the volatile saturated perhalo chlorofluorocarbons, and that would include fluorocarbon 13 and fluorocarbon 112, and so on.

Then I would like to go over to the overhead and show two slides here. I will go over and show those to you. These overheads are designed to show you the security or lack of security that we can expect from the Montreal Protocol.

What we have here is a graph of the amount of chlorine that has been in the atmosphere, and will be in the atmosphere. This colorless part down below is the natural amount of chlorine. The red part is the amount of chlorine that has gone into the atmosphere up to the present time from man.

In about 1970, the amount of chlorine from man became about equal to the natural chlorine, and since that time it has been going up in a very steady fashion so that we have gone from about 7/10th of a part per billion in 1950 to maybe 3.6 or 3.7 parts per billion now.

The protocol does not come in until 1994, and then it calls for only a reduction of 20 percent, so there is almost no change in the amount of chlorine in the atmosphere from what we would get just by the normal continuation of atmospheric release frozen at 1986 levels. The protocol is the lowering up through here in 1994 and beyond.

The orange part is the amount that would be cut out by the protocol. Even in the Year 2010, the protocol makes very little change in the total amount of atmospheric chlorine. We are at 3.7 parts per billion. We are going to go to 5 parts per billion almost before the protocol even begins to cut in, and we will continue to increase even then.

I have a slightly different version in this slide, which covers the same material. The black part through 1974, in fact, shows how far we were at the first warning about the chlorofluorocarbons' effect on ozone.

While we have been waiting and investigating, the amount of chlorine in the atmosphere has gone up by the amount shown here to the red, from about 1.7 to 3.6 parts per billion. This is where we would go with the protocol, up to that point, before there is any change. This is with the freeze.

It is much easier to talk about controlling emissions than it is to talk about controlling the amount of chlorine in the atmosphere, because the amount that is in the atmosphere is there to stay with times on the order of 100 years. The amount of chlorine that is there is being added to. The proposal in the protocol is that we not change the amount that is going in, but keep it at a constant level. However, this means a constant increase well into the 1990s.

This blue part is the effect to be observed if we, in 1994, instituted an 85 percent cutback, not a 20 percent cutback. Even with an 85 percent cutback, the amount of chlorine in the atmosphere is going to continue to rise on into the time period of the 21st Century.

For these reasons, I think that we cannot afford to wait until 1994 to institute drastic reductions in emissions of chlorofluorocarbons and that, when we do put those restrictions in, they will need to be much more stringent than 20 percent or 50 percent.

We have to reduce emissions drastically and soon so that we just simply do not add to the total burden of chlorine in the stratosphere.

Thank you very much.

Senator BAUCUS. Thank you, Dr. Rowland.

Our final witness is Dr. Michael Oppenheimer of the Environmental Defense Fund.

STATEMENT OF DR. MICHAEL OPPENHEIMER, ENVIRONMENTAL DEFENSE FUND

Dr. OPPENHEIMER. Thank you, Mr. Chairman.

At the beginning of the hearing today, you asked a question which I might paraphrase as: What are the current environmental implications of the ozone depletion in Antarctica, and what are the implications of the ozone hole for populated latitudes now or in the future?

From the base of understanding that has gone before me in this hearing, let me do a little projecting. Such an effort is always risky; but in this case the effectively irreversible nature of ozone depletion demands that we make such projections, although, of course, such projections are no substitute for more research.

The observations lead me to conclude the following general conclusion: current atmospheric levels of chlorine present substantial risks to the environment. My specific findings are as follows.

Increasing Antarctic springtime ozone depletion would not occur in the absence of halocarbon emissions.

Seasonal ozone depletion, perhaps related to depletion in the vortex, has already occurred more broadly in the southern half of the southern hemisphere. Ozone poor air could be mixing out of the vortex and causing depletion at other latitudes. This, by the way, refers to the purple blob on Dr. Watson's figure, which could be a source of ozone depletion for populated areas, ozone poor air moving out of the vortex. As Dr. Anderson said, the scale of depletion in Antarctica has potential significance well beyond the vortex.

Biological consequences of seasonally enhanced ultra-violet radiation due to ozone depletion could be affecting the Antarctic marine food web now. I am going to make a more cautious estimate of the increase in ultra-violet radiation at the surface than Dr. Wilkniss's upper-bound case. Based on some calculations that were done Ann Thompson at NASA, one could estimate that the current increase in ultra-violet flux at the surface, when the ozone hole is at its deepest, is about a doubling. It is doubling of a relatively small number but, to put it in context, it would be equivalent to increasing the ultra-violet radiation at the surface here at mid-latitudes by about 20 percent. It is a very, very big increase from the point of view of biological systems.

The ozone hole will be with us for a century, although its intensity will vary, as long as chlorine concentrations remain at current levels at least, so any biological consequences of Antarctic depletion will be long-lived.

In general, the hole can be expected to deepen if atmospheric chlorine increases; in other words, as Dr. Rowland has just shown, for as long as significant CFC emissions occur.

It is rather astonishing to consider, in this respect, that with regard to biological consequences the horse may have already left the barn.

The growth of other greenhouse gases and of aerosol particles in the atmosphere may create conditions in the future which are favorable to enhanced ozone depletion at other latitudes. This "fast kinetics" is a byproduct of stratospheric cooling and increased stratopheric water accompanying the greenhouse effect.

It is worth noting, as Dr. Rowland did, that such enhanced or fast kinetics could potentially be occurring, albeit at a lower level than in Antarctica, already at this time.

The ozone hole was a surprise. I think that we can expect nastier surprises of this sort in the ocean atmosphere system in the future for as long as we add ozone depleting and greenhouse gas emissions to the atmosphere. We have had the rather astonishing experience that part of the earth's life support system now appears capable of large and rapid change due to human disturbance.

We have to enhance our capability to understand these surprises and in this respect I would underscore support for the International Geosphere-Biosphere Program (global change) a major scientific effort to understand these problems.

We should take the ozone hole for a warning. Even current atmospheric chlorine levels bear uncertain risk of unacceptable consequences. The only sure route to avoid such consequences is the rapid elimination of CFC and other halocarbon emissions, as much as possible and as fast possible.

The ozone hole puts humanity in an extraordinary situation with regard to risk and uncertainty. If we should be fortunate enough that the hole does not generally affect areas outside the vortex, and that it is not damaging biological systems in Antarctica, then at least it has a symbolic value, which in the end may override its damaging consequences.

The appearance of the hole was probably the most significant factor in accelerating the move toward the ozone protocol. As we have heard, the ozone protocol isn't the last word, and my testimony contains some suggestions, which the Senator might pursue for improving it.

But the ozone hole will stand for decades as a redlight flashing a warning every spring against too much tampering with the atmosphere, and that is a warning we should not fail to heed.

Thank you.

Senator BAUCUS. Thank you very much, Dr. Oppenheimer.

Gentlemen, I would like to make a series of points and I would like you to tell me whether you agree or disagree with them. Since our last May hearing, and as a consequence of this recent expedition to Antarctica, it seems to me that we could make certain statements as to what we now have learned.

Number one, whereas before the expedition, at that time there was debate as to what caused the hole, there were various theories, the meteorological theory, the chemical theory, and a third was sunspots and other natural phenomena, is it safe to say that it has now definitely been established that CFCs are a very significant cause, perhaps not the sole cause but a very significant cause, of ozone depletion?

Is there anyone who disagrees with that statement?

Dr. MCFARLAND. They are contributions, yes, to some extent. Meteorology and chemistry both contribute to the formation of the hole. We cannot separate the relative contributions. They are contributors, yes, to some extent.

Senator BAUCUS. Apart from the question of industry versus nonindustry analysis of this, it just seems to me that that cause has very definitely been established. It may not be the sole cause of the ozone hole, I grant you, but I think that it is fair to say that it has been definitely established that CFCs are a primary cause, there may be other primary causes, but certainly a primary cause of ozone depletion in the Antarctic.

Dr. OPPENHEIMER. Senator, I think that the best way to say it is, without chlorine in the atmosphere, we would not have ozone depletion anywhere near the magnitude that we have, if at all.

Senator BAUCUS. A second observation. The second observation is that it is also now established that the amount of ozone in the stratosphere is now depleting. The ozone in the stratosphere is now less than what it was a year or two ago. I understand that the reduction in the Antarctic amounts to about a 1 percent reduction ozone worldwide. Is that a fair statement?

I see no one leaping to disagree with that.

Mr. MCFARLAND. You are not talking about the northern hemisphere. For example, are you taking what is missing out of the Antarctic and averaging it over the globe?

Senator BAUCUS. Correct. Is that roughly a fair statement? I wouldn't want to put words in your mouth.

Senator STAFFORD. Mr. Chairman, maybe I am confused here, but I got the impression from Dr. Rowland's testimony that globally there might be something on the order of a 5 percent depletion of ozone. Was I mistaken?

Senator BAUCUS. That is right. I am trying to be fair and conservative here. What about that, is it more than 1 percent?

Dr. WATSON. I think that there are a couple of issues here. One of the questions that was asked in the letter to me was to give you a status report on the Ozone Trends Panel.

Many scientists will be meeting in Switzerland in two weeks time to finalize that report, therefore, the report will be available to Members of the Senate and House of Representatives soon after the meeting in Switzerland, hopefully by the end of this year.

The key question that we will be asking ourselves: is the satellite data that is reported to have shown as much as a 7 percent change in ozone globally correct, or is the ground based Dobson network data that shows 4 or 5 percent since the late 1970s correct?

It is premature for me to give you the results at the moment. There is no question that there appears to have been a significant change in ozone since 1979 to 1986.

The exact cause of the change is something that we will also report on. Possibly some of it is due to natural variability, possibly some of it is due to fluorocarbons, and possibly some of it is due to a pure dilution effect from the Antarctic ozone hole, which is what I think you are referring to here. To restate it, you have an ozone hole in Antarctica, and just that hole itself, by diluting the southern hemisphere, could have global ramifications. One percent seems a little high for just that dilution effect, but parts of a percent would seem at least reasonable.

Senator **Baucus**. Without getting to the causes of the depletion, the fact is that there is a depletion of ozone worldwide in the magnitude of roughly what?

Dr. **Watson**. Ozone has probably shown a change of several percent since the late 1970s.

Senator **Baucus**. Three to 7 percent, perhaps.

Dr. **Watson**. Yes, the key question is, is that natural variability or is it due to fluorocarbons.

Senator **Baucus**. I understand that it is a key question.

Dr. **Watson**. It is key question which we hope to address in our report.

Senator **Baucus**. Dr. McElroy, do you have a comment on that?

Dr. **McElroy**. If you do a very simple estimate of the direct impact of the Antarctic phenomenon, if we have a 50 percent reduction in 10 percent of the southern hemisphere, and we average that to the entire southern hemisphere, that would correspond to a 5 percent reduction. Averaged to the globe, it would correspond to a 2.5 percent reduction.

Just by that very simple scaling, one arrives at a number, which is not very different from the number that you got.

Senator **Baucus**. Thank you very much, sir.

Senator Chafee.

Senator **Chafee**. Thank you, Mr. Chairman.

I would like to pursue this. First of all, everybody agrees that the ozone layer in the winter and in the spring in the Antarctic has been depleted. There is no argument about that, is there? Then when you move toward the summer, the natural conditions are restored.

My question is: When the natural conditions are restored, does it go back to whatever normal is? Does it go back to where it was the prior year, or does it end up lower?

Dr. Anderson.

Dr. **Anderson**. Thank you for selecting me to answer that.

Senator **Chafee**. I will give everybody a chance.

Dr. **Anderson**. The testimony here has clearly stated that there is a volume within the vortex within which ozone is eliminated forever. The fact that ozone returns to essentially normal concentrations after this vortex region breaks down does not represent the small 2.5 percent that Professor McElroy mentioned, which is forever taken out.

The question revolves around careful calculations of self-healing, of changes to alter this, and these need to be carried out with care, but the clear, first order implication is that that ozone is destroyed and is destroyed forever. So it is subtracted from the global bank of ozone.

Senator **Chafee**. Does everybody agree with that?

I don't think that Dr. McFarland would agree with that, but Dr. Rowland.

Dr. **Rowland**. Dr. Farman, in his initial report that called attention to the antarctic ozone hole, also pointed out that there was less stratospheric ozone over Halley Bay, the place where they measured it, all during the daylight period. It was a very sharp drop in the October and early November period, but there was less stratospheric ozone over Halley Bay during December, January and February.

Senator CHAFEE. That ties in with your Arosa findings in your report, doesn't it?

Dr. ROWLAND. I think that there is evidence. What Bob Watson just said, if you look at the ground-based stations, there is less ozone by several percent. If you look at the satellite, they say up to 7 percent. The question is not whether we have lost ozone, but how much ozone we have lost, and trying to allocate the responsibility for the individual losses.

With the ground-based stations, this is, in my view, not a question of whether or not there is a solar cycle effect mixed into it, because the ground-based stations go back for 25 years in two cases and for 55 years in the third case. The solar cycle effect of 11 years is wiped out in those comparisons.

Senator CHAFEE. Is there any argument that the ozone depletion was clearly linked to the increases in chlorine, that was your point, Dr. Anderson.

Dr. ANDERSON. Right.

Senator CHAFEE. I am not singling you out. Your name starts with "A" and that is why you come first. That is what you said. You said that there was no question, and your graph showed it, the blue line, as the chlorine went up, the ozone came down.

Dr. ANDERSON. That is correct. The key point is that in the period just after the polar winter, there is a positive correlation between the ClO radical and ozone. In the next three weeks that transitions over to a very powerful correlation during which the rate of ozone disappearance is commensurate with the calculated removal rate of ozone based on the observed ClO concentration. That is very strong evidence.

Senator CHAFEE. Would anybody argue with that?

This is important stuff, folks, and now here is your chance. Silence is assent in the way I am scoring it here.

Dr. Watson.

Dr. WATSON. I think that all scientists who went to Punta Arenas would agree with what Jim Anderson just said. At the maximum altitude of the ER2, which is about 18.5 kilometers, there was enough ClO, assuming that we have the laboratory chemistry about correct, to say chlorine destroyed ozone.

One key question would be, though, whether the ozone decrease observed at 14 to 16 kilometers was caused by chlorine. Dr. Jim Anderson saw a very sharp gradiant of the amount of chlorine, ClO with altitude. So there are still a few unanswered questions, and one of them is: Could chlorine also be responsible at the lower altitudes?

I think that this is still an open question, but around the 18-kilometer region, I don't think that there is any question that chlorine is a major cause of the destruction of ozone.

Senator CHAFEE. My time is up, but I will just ask one question, if I may.

Dr. Wilkniss, I think both you and Dr. Watson said that you weren't able to determine damage to humans, at least the group that were doing the Antarctic experiments, when you encountered this tremendous depletion of the ozone, and the ultra-violet rays were coming. Did you test those and did those record far higher?

Dr. WILKNISS. Senator, the problem is that we did not have UV, ultra-violet, monitors in place last year, and the precipitous drop this year caught us by surprise. We have one such instrument operating at the South Pole, but it did not start until late October, when the sunlight and, therefore, the UV got to the South Pole. Most of our people were around the coast, McMurdo Station, where we did not monitor the UV, and where the impact potentially is much greater.

Senator CHAFEE. The impact would be much greater where, did you say, at McMurdo?

Dr. WILKNISS. At the coast where the sunlight comes early, and the sun shines at a steeper angle on the people, there is more UV impact when the ozone hole is at that station.

Senator CHAFEE. My time is up. Thank you, Mr. Chairman.

Senator BAUCUS. Senator Stafford.

Senator STAFFORD. Thank you, Mr. Chairman.

Dr. McFarland, I am going to turn to you for a couple of questions. On page 3 of your testimony, you say that "recent computer modeling studies of the impact of the steps show," and so on. Whose modeling was that?

Dr. MCFARLAND. That was the modeling supported by the Fluorocarbon Program Panel, and it was performed by the Atmospheric and Environment Research.

Senator STAFFORD. My recollection is that, of the various CFCs that are in use, 22 was the least toxic so far as ozone was concerned. Am I correct in that?

Dr. MCFARLAND. Most of the 22 does not reach the stratosphere.

Senator STAFFORD. I also recall earlier testimony in front of this committee that there was a CFC under development, 134A, which, as a layman, I got the impression might be inert as far as ozone was concerned. Is that CFC currently under test for toxicity and so on?

Dr. MCFARLAND. I should point out that I am an atmospheric scientist consulting on this issue, on the science issue, and you are getting outside of the area of my expertise. I would be glad, if you provide me with a list of questions, to see that those questions do get answers.

Senator STAFFORD. All right, Doctor, if you are not an expert, believe me, I am not either, but I am going on the testimony of experts the last time that they were in front of this committee.

Dr. MCFARLAND. Yes.

Senator STAFFORD. It seems to me that one of the benefits we might derive from the Montreal Agreement would be pressure to develop CFCs, or something like them, that are inert as far as attacking ozone in the stratosphere is concerned. I think that this is an important avenue and something this committee ought to be quite interested in.

Dr. McElroy, I think you testified, and maybe this is going over previous territory, that there has been a general depletion of O3 throughout the globe. Is that correct?

Dr. McElroy. In response to the chairman's question, I simply tried to scale the 50 percent reduction over Antarctica to what the arithmetic might suggest might be the global volume.

Senator Stafford. Dr. Oppenheimer, on page 4 of your testimony, you pointed out that at altitudes above 20 kilometers, in the mid-latitude stratosphere, solar ultra-violet radiation causes the fragmentation of molecular oxygen into atoms, and that that does form ozone.

Speaking again totally as a layman, I gather that there is a constant replenishment of ozone in the upper-atmosphere as a result of the chemistry you described on page 4.

Dr. Oppenheimer. In general, at the middle latitudes, the replenishment of ozone, of course, during the Antarctic spring the sun is low and that replenishment doesn't operate. The question really is: Could that replenishment restore ozone lost in Antarctica.

Senator Stafford. That would have been my next question.

Dr. Oppenheimer. That is a good question, and I think the answer you are getting from this panel is, maybe yes, maybe no, that was the self-healing that Dr. Anderson talked about. It looks like you could expect up to a 2.5 percent depletion globally of ozone if the Antarctic hole got mixed up with all the other ozone in the world before this sort of self-healing could occur.

More specific than that is hard to be at this point, except that I will say, I think that, at least in the southern hemisphere, there is now depletion due outside of the vortex due to this mixing.

Senator Stafford. Thank you.

Dr. Watson, you said that there is evidence that meteorology is playing, in your words, "some role, at least some role, in Antarctica." Could you suggest what you meant by that?

Dr. Watson. Yes. We observed, as I showed you in the figure 2, as much as a 10 to 15 percent change in ozone over the Weddell Sea, which is about 3 million square kilometers all within 24 hours. It seems very difficult to give a purely chemical explanation.

We believe that ozone moved in from mid-latitudes, the lower stratosphere at mid-latitudes which is relatively low in ozone. A low pressure system formed just around South America and effectively transported air from the middle latitude into the Weddell Sea area and it, in essence, looked like an ozone hole.

That is our best evidence that there is a purely meteorological formation of the ozone hole at some time. We just can't believe that in 24 hours, you could actually force the chemistry to go fast enough to destroy so much ozone.

Senator Stafford. Thank you very much.

Thank you, Mr. Chairman.

Senator Baucus. Thank you, Senator Stafford.

Senator Pressler.

Senator Pressler. Thank you, Mr. Chairman.

I would like to explore a little bit more what has been covered in part here about the Antarctic. I guess, if that air would mix, what is the meaning to the rest of us, so to speak?

I would like the panel to describe how that air would mix and how that would probably happen. I can see the problem in the Antarctic, but how quickly would that get to the rest of us?

Also, what is the cumulative impact of virtually destroying that much ozone year after year?

After 20 or 30 years, how much of the planetary ozone has been destroyed?

Do I see any volunteers on that range of questions?

Dr. McElroy. I will try, using the stock market, perhaps, as an analogue.

Suppose the value of IBM goes down by five points, and all other stocks in the Dow Industrial Average remain unchanged, since the index is an average of the total number of 30 stocks, including IBM, when you mix them, they will go down. In the same sense, in the atmosphere, when you mix in undepleted air from the outside with the IBM Antarctic air, the total level goes down.

Dr. McFarland. You are talking to a panel of chemists here. I think you need an dynamicist here to adequately address this question, or a meteorologist.

Senator Pressler. What was the first word?

Dr. McFarland. A dynamicist, or a meteorologist that knows exactly how this winter vortex breaks down when the springtime comes, because about one-seventh of the total air in the stratosphere is transported to the troposphere every year, so it is a question of whether that air is just diluting by mixing with the rest of the stratosphere, or actually mixed out of the stratosphere anyway.

I think there was one experiment run in a three-dimensional model of the atmosphere that indicated that the dilution effect was fairly small, but that is clearly an area of research that needs to be further investigated.

Dr. Wilkniss. Senator, I would like to second what Dr. McFarland said.

This, to me, is the most unknown part of the Antarctic ozone hole, the dynamics of the Antarctic atmosphere. It is so difficult to come by because we don't have any stations, meteorological stations, and we have very few meteorological satellites that read out over the Antarctic.

What Dr. McElroy described, the wall, the vessel, is very well known in storm systems, in the intertropical conversion zone, between the stratosphere and the troposphere, and in frontal systems that pass right through Washington. They very sharply divide what is going on in the atmosphere.

What you find in the Antarctic is that you have a tremendous air mass over a tremendous ice mass. It cools down, it begins to rotate during the winter, and it forms kind of a beaker, like in the chemical laboratory, and in that chemical beaker the reactions take place. It is very well defined and it is of such magnitude that the forces that come from the outside, the storm systems that come from the warmer regions, cannot destroy it.

It exists therefore, a long time. But this is a lot of conjecture. I think that some of the experiments that have been done in the Arctic that deal with the intrusion of the stratosphere in troposphere, we see indirectly in the Antarctic. It is a very interesting effect, namely, in McMurdo, on the ground, the ozone level goes up, and we find that air from the stratosphere has come down.

Again, we do not have enough stations or airplanes or balloons or satellite information to piece the whole picture together for you.

I think that this is the most pressing research need we have in the next few years.

Senator **Pressler**. Thank you very much.

Thank you, Mr. Chairman.

Senator **Baucus**. Gentlemen, an obvious key question, and one that Dr. Watson phrased, is: What significance does all this have for other latitude, particularly, shall we say, for temperate latitudes. I think Dr. Watson said that we just don't know yet, and that we have to conduct further experiments, et cetera.

For a moment here, if we could discuss, based upon what we do know, that is, ozone depletion and the degree of ozone depletion over the Antarctic, what implications that does have for other latitudes.

Dr. Rowland, you testified that perhaps the heterogeneous chemistry or the surfaces at temperate latitudes may also be such that the same kinds of phenomena of ozone depletion may be occurring. Would you expand on that please? What did you mean by that?

Dr. **Rowland**. The occurrence of chemical reactions is frequently aided by having a surface on which the participating reactants can sit down and get together. It is catalytic in nature. It is very common in the chemical manufacturing industry to try to find the best surface on which the reactions will occur.

What we find is that for stratospheric reactants such as chlorine nitrate, that surfaces greatly assist the reaction of chlorine nitrate with water, and they greatly assist the reaction of chlorine nitrate with hydrogen chloride.

These reactions seem to be the predominant reactions that are converting chlorine in the Antarctic into a form which makes them more reactive when the sun comes up. And these reactions seem to be occurring on stratospheric particles present in the Antarctic.

We certainly know from work in my laboratory that we were unable to find any surface on which these reactions didn't occur. I think that it is very hazardous to assume that the surfaces that are known to be there in the temperate and tropical latitudes, that these will turn out to be inert, when those surfaces which we have looked for to be inert are not in the laboratory. I think that these reactions probably occur on all kinds of surfaces, including those in the temperate and tropical zones.

In the temperate and tropical zones, we don't have all of the special meteorology of the Antarctic. Therefore, we don't have ozone-depleting chlorine chains running unhindered for a period of several weeks. But we will have short chlorine chains that will chew up a little bit of ozone each time they happen, each time these reactions occur.

So I think we have a long-term contributing reaction very possible in the tropical and temperate zone stratosphere that will augment to the loss of ozone there by reactions that are analogous to, but not as rapid as observed in the September period in Antarctica.

Senator **Baucus**. Dr. Watson, do you have a comment?

Dr. **Watson**. Yes. My comment would be, I don't disagree with anything Dr. Rowland just said. However, the question is proving it. I think what I said earlier is that a small amount of additional research would be able to verify or disprove whether or not these processes are occurring at mid-latitudes.

In other words, even some of the data already collected by scientists such as Jim Anderson in test flights over California should allow us to last for elevated levels of ClO at altitudes near 20 kilometers. We should also be able to do additional experiments to see whether or not there are elevated levels of ClO coincident in areas where there are aerosols at mid-latitudes. It is this type of data that needs critical examination to see whether or not there is any elevation of ClO at mid-latitudes.

Senator BAUCUS. Dr. McElroy.

Dr. MCELROY. Of course, the answer to the question must involve a certain amount of guess work, so let me offer my guess.

I think that the critical factor in the heterogeneous chemistry involves the incorporation of hydrogen chloride in the ice. It would be my guess that that chemistry per se will not occur at mid-latitudes where there are aerosols in the stratosphere. But I think that the issue for the northern hemisphere goes back to the Polar region. I don't think that we would expect to see a dramatic hole in the Polar region, but I think that the chemistry that occurs in the Antarctic should occur in the North Polar region as well.

The difference between the South Pole and the North Pole, namely, the absence of the containment vessel, works both ways. If you start releasing to the mid-latitudes from the North Polar region air, which is conditioned for fast ozone loss, that could have an effect which shows up at mid-latitudes and may, indeed, be part of the apparent reductions that Dr. Rowland talked about.

In my opinion, the most important, urgent experiment to be done is to, in fact, repeat the Antarctic Experiment, but to do it in the North Polar region.

Senator BAUCUS. You anticipated one of my next questions.

To summarize what the last panelists have said, it seems that, at least theoretically, the heterogenous chemistry at the latitudes, particularly polar latitudes, is sufficiently similar to expect some of the same chemical reactions to be occurring, although, as Dr. Watson said, we don't know that, and it cannot be proved. We, therefore need more experiments or data to verify whether or not that exists.

Turning to you, Dr. Watson, since, as I understand it, you basically had a lot to do with martialling the resources for the Antarctic Expedition, what should the next experiments be; where do we go from here to determine whether or not this phenomenon is spreading to other latitudes, and the degree to which it is becoming an ominous threat to the environment?

What experiments next make most sense?

Dr. WATSON. I think that the first thing to do is to fully analyze this incredible wealth of chemical and dynamical data that we have just collected at Punta Arenas, and the data that the scientists at McMurdo have just come back with. I think that we should spend the next six months critically analyzing all of that data, both meteorological and chemical. At that stage, I believe that we will be much wiser to decide where to go.

I don't disagree with Professor McElroy that doing an experiment around the North Polar regions makes some sense. As I said earlier, it might make some sense just to do some work at mid-latitudes, to look for elevated concentrations of ClO if, indeed, processes such as that involved in his proposal should go.

I think what we should do is really spend six months carefully analyzing this data, and at that stage make a very thoughtful decision as to where to go.

These expeditions are very time consuming, as well as being very costly. Scientists end up spending months, and I mean six months of their life away from families, preparing for the experiments and conducting the experiments. Therefore, we shouldn't go on wild-goose chases. We should look carefully at what we already have, and then decide whether we need to do a North Polar experiment or whether we just need to do a mid-latitude experiment.

The one thing we have decided is, we will not go back to Punta Arenas next year insofar as we don't, at least at this moment, know what additional information we would get by just redoing the same experiment.

We have not given up on the idea of going back to the South Polar region in 2 years time, and that might well include trying to do a mid-winter set of experiments as well as doing a springtime set of experiments, trying to understand exactly what is occurring during the polar night, what conditioning of the atmosphere is taking place.

So I believe at the moment that it is a little premature to give you a solid answer. In the February timeframe, when we have one of our first workshops, or in the April/May timeframe, when there will be an open workshop for scientists from all over the world, in that timeframe, we will carefully look at all the data, and after a lot of discussion with all the scientists involved, we will decide how the agencies, i.e. NASA, NOAA, NSF, CMA and others would like to conduct the next set of experiments.

Senator BAUCUS. Before I turn to Senator Chafee, here is an opportunity for any of the other panelists to get their two bits in. What experiments do you think make most sense?

Dr. OPPENHEIMER. I just wanted to ask Bob. Did you say that there had to be a choice, essentially, between doing a mid-latitude experiment and a north latitude experiment and, if so, what is the limiting resource? Is it money? Is it the number of scientists?

Dr. WATSON. There is only one set of scientists at the moment that have experiments of proven high quality to conduct the aircraft campaign. It may well turn out to be a choice of do we conduct mid-latitude flights or polar flights.

There are only so many aircraft hours available, and there are only so many hours in the day to conduct the experiments and to carefully analyze the results. So there may be a choice.

It could well be that we could be more sensible and decide how to do mid-latitude flights and a polar expedition all at once. But we need to think about it very carefully.

One thing that I didn't say is that there is a large amount of laboratory work that still needs to be done, and it is on-going. The scientists that work in the laboratory have already seen some of the results that we have displayed through the press conference.

It is very clear that there is a lot of uncertainty in the chlorine chemistry, both in the gas phase and in the heterogeneous surface gas interface. So those scientists are already readily looking at laboratory studies to try and minimize the uncertainties that we currently have in our understanding of the chemistry.

Senator BAUCUS. Dr. Wilkniss.

Dr. WILKNISS. Mr. Chairman, I would submit the following opinion. I agree with what my colleague said, but I feel that the U.S. scientific community and the U.S. scientific agencies cannot shoulder this burden alone.

We have pushed our systems to the limit in the Antarctic and among the agencies to cooperate and come up with the people, with the equipment to make it work. I must say, up to now, it has been a miracle how well it has worked. But if you look at the size of the Antarctic, it is not enough. We have to enlist the cooperation of the other countries.

The Soviet Union, for many years, has made excellent measurements of ozone, and so have the Japanese. The Germans have developed ship-borne equipment to look at the ozone, and so forth. The time has come, and the Antarctic Treaty and SCAR, the Scientific Committee for Antarctic Research, provide the mechanism for us to show the leadership and enlist our colleagues to join a coordinated program among all the nations in Antarctica.

I don't think that we can do it alone. There are too many problems. We do not have the scientists. We are often told, why don't your scientists do this, but there is only a handful of leading scientists and they are like an ambulance, they are required everywhere.

Also, for political reasons, the approach to this problem needs to be international, because the politicians in other countries will want to hear from their own scientists as to what decisions to make.

The same applies for the North Polar region, a much more difficult proposition, because you do not have a firm continent around the North Pole where you can set up stations. You are dealing with a much smaller platform, so to speak, Greenland and Spitzbergen, but you have outstanding scientists, especially in the Scandinavian countries, in meteorology, atmospheric dynamics, and in atmospheric chemistry. I think that it has to become a global orchestrated effort, otherwise we will not succeed.

Senator BAUCUS. Thank you very much.

Senator Stafford.

Senator STAFFORD. Thank you. I think that most of my questions, Mr. Chairman, have been answered now.

Dr. Rowland, my recollection is that CFCs in the upper atmosphere and the stratosphere have a life approaching 100 years. Am I correct in that?

Dr. ROWLAND. The current estimate from measurements at the surface level is that the average lifetime of fluorocarbon 11 is about 75 years, and the average lifetime of fluorocarbon 12 is more than 100 years in the atmosphere.

Senator STAFFORD. So that whatever we have up there now is going to be around for approaching 100 years, from 75 to 100 years.

Dr. ROWLAND. Much longer than that.

Senator STAFFORD. That is why the content of the upper atmosphere is going to continue to have a high percentage of CFCs; am I correct there?

Dr. ROWLAND. That is correct.

Senator STAFFORD. I gather, from the testimony here today, that the Protocol from Montreal, although an encouraging development in view of the attitude of many countries a few years ago, is woefully inadequate in addressing the situation we are now facing as a globe. Is that correct also?

Dr. ROWLAND. In 1974, when Molina and I first suggested there would be a chlorofluorocarbon effect on ozone, there was about 1.8 parts per billion of chlorine in the atmosphere. At that time, it was suggested that if only we had three more years of scientific research, we could get the answers.

We are now 13 years into that 3-year period, and we now have 3.7 parts per billion of chlorine in the atmosphere instead of 1.8 parts per billion and, as you just heard, we need another three more years to solve the current questions.

Now, I am a scientist and I can ask questions about the atmosphere, too, and I have been, and I find some very interesting questions that I can get an answer in the next three years, if only I have money to do it. I don't need any more money to know that the chlorofluorocarbons have accumulated dangerously and that we ought to be limiting them.

Senator STAFFORD. Thank you, Doctor.

Mr. Chairman, there is some legislation that has been introduced on this subject. Maybe it would be appropriate to think about some further hearings and a markup in connection with that legislation.

Senator BAUCUS. That is right, there is some legislation that you, Senator, are a very strong advocate, proponent, and author of that legislation. I think it would be a good idea.

Senator STAFFORD. I thank you, sir.

Senator BAUCUS. Senater Chafee.

Senator CHAFEE. Thank you, Mr. Chairman.

I would like to pursue this. Is anybody thinking about what you might call "What if"?

What if this annual drain of 1 percent—I don't know whether you have agreed on what the annual drain is, but let's say that it is 1 percent. How long can we keep this up?

Let me address this to you, Dr. McFarland. You indicated in your statement that we are on the right track, that the Montreal Protocol is fine, that it is proceeding at the right speed. Yet, Dr. Rowland, and I agree with Dr. Rowland, is sounding a far greater alarm here than you are. Hadn't we better do something about these CFCs now?

Dr. MCFARLAND. In drafting the Montreal Protocol, the policymakers took into account the best scientific information available to assure protection of the ozone layer. They also allowed for a review clause. It is a living document, as I said.

This data that we have heard about today is preliminary. The scientists will continue to analyze it. Within the next year, it will be fully analyzed and assimilated, and we will know much better. This is very much an international issue, which must be dealt with internationally.

Senator CHAFEE. I agree with that. As those who are in the audience who have been here know, and as the members of this subcommittee know, the approach of the committee has always been that it is preferable to have an international agreement so that we can get everybody doing it, the fear being that if the United States moves at a faster pace that the other nations will say: Why worry, the United States, which is producing 33 percent of the CFCs, if they are reducing theirs way down, it means that we don't really have to do very much.

I, for one, wish to proceed in an international approach, but I get much more of a sense of urgency out of this than some have voiced here. I don't get much consolation that by 1994, we will have to go down by 20 percent. That is a long way from now, 1994, and all we get now is a stabilization.

The CFCs are going up. Dr. Rowland said that they have a life span in the atmosphere of 75 years. I assume that you are meaning that in the stratosphere it is a much greater extension of that.

Dr. ROWLAND. The amount that is in the stratosphere will follow the amount that is in the atmosphere generally, so that 75 years is the lifetime.

Senator CHAFEE. The lifetime is the same.

Dr. ROWLAND. Overall.

Senator CHAFEE. What do you say about that, Dr. Watson?

I know you say that we want to look this over carefully, but I am getting worried.

Dr. WATSON. I think it is correct, you should be worried.

I don't think there is any question whatsoever. That if one wanted to eliminate the observed hole in ozone in Antarctica, the first step would be to remove all the chlorine in the atmosphere, and the only step we can do for that is to stop any future emissions. There is no question whatsoever.

If the goal were to effectively return the Antarctic atmosphere——

Senator CHAFEE. Not too fast now, because I have trouble following you. I don't know about the Soviets in the audience.

Dr. WATSON. I think the Soviets left actually, sir.

If the goal were to attempt to return the Antarctic atmosphere to its pristine state of, we will call it, normal ozone, then indeed the only hope for doing that would, indeed, be to have a complete cessation of the production and emission of fluorocarbon and halons immediately. Even then, it would probably take several hundred years for the system to go back to normal. It depends on how non-linear the chemistry is in Antartica actually.

I believe the Montreal Protocol is a very excellent first step. It took a lot of negotiation within the United States Government and, of course, internationally. I think that it is a very wise step, and I believe that it is essential that the Montreal Protocol be ratified as soon as possible.

I believe that at that stage, it would then be prudent for policymakers worldwide to reevaluate whether or not that is an adequate measure, whether or not one needs to go further. At this moment in time, I need to think much closer, myself personally, on what does the Antarctic ozone hole mean from my perspective for global ramifications.

As I said, if you want to protect the Antarctic atmosphere, there is no question, one has to go much further than the Montreal Protocol, and it will take many decades to see that hole recover.

Whether there will be global ramifications, i.e. that same mechanism occurring at other latitudes, I am not personally convinced whether there will or will not. My belief is that within the next six months we have an incredible amount of information to address that part of the issue.

Senator **Chafee**. If you could just repeat that one little part. You are not personally convinced that what has happened in Antarctica is going to be repeated globally. Am I correct?

Dr. **Watson**. Correct. I am not yet convinced. It is certainly a possibility, and I think that we have to look at the suggestions of both Professor Rowland and Professor McElroy. I think that they are both excellent comments.

I think that the scientific community has worried about it. I believe that by analyzing this data within the next six-month period, we will have a much better feeling for whether or not these same mechanisms that are causing the Antarctic ozone loss will occur at other latitudes.

It is not yet clear to me that they will occur at other latitudes, and I would like to at least go through the scientific process of critically analyzing these data and submitting them to peer review, and see what the global ramifications are.

Senator **Baucus**. I would like to follow up on that. You say that you are not completely convinced one way or the other. What is your best guess?

Dr. **Watson**. As Dr. Rowland has already said, we certainly won't see the same magnitude effect that we see in Antarctica. There clearly could never be that kind of special meteorology at other latitudes.

The question is: Could it occur even 1 to 2 to 3 percent of the same rate, because even then it would give you a 1 or 2 percent depletion globally, and that would be quite significant and important.

I will be quite honest. I honestly don't know. It is not clear to me, and I think Professor McElroy said this, it is not clear that the same heterogeneous process occur on sulfuric acid surfaces as on the ice cloud nitric acid surfaces in the Antarctic atmosphere. It is not clear to me.

Senator **Baucus**. I understand that it is not clear. I am just asking for your best guess of the degree to which ozone depletion might occur?

Dr. **Watson**. I think Professor McElroy made a good point. I think we should try to differentiate between facts and personal opinion.

Senator **Baucus**. I am asking for your personal opinion, that is all. I know that you are a scientist.

Dr. **Watson**. I don't think that there will be significant effects globally. Based on the same mechanisms occurring, I don't think that there will be. In six months, though, I may totally change my mind when I see evidence.

Senator **Baucus**. Dr. Oppenheimer.

Dr. **Oppenheimer**. A few things need to be pointed out here. First of all, even if these fast kinetic mechanisms aren't occurring, there is ozone loss occurring due to the standard chemistry at the midlatitudes. That ozone loss is, from an environmental point of view, unacceptable, so that there is good reason to try to eliminate CFCs as rapidly as possible. But I am not as sanguine as Dr. Watson is about trying to unravel these questions that quickly.

So a prudent course, in any event, would move us in the direction of assuming the worst and moving towards eliminating CFCs, and changing our direction if it turns out that we got lucky.

I want to add that I think we are already in a fine pickle just on the basis of the Antarctic observations. We have taken a big chunk of the world, denuded it for a good part of the year of ozone, and increased the flux at the surface of ultra-violet by a substantial amount. It is bound to have effects on ecosystems down there, which in other directions we are fighting very hard to protect.

I don't see any excuse at all for slowing down the train and waiting for results. By all means, let's put as much money into this science as possible so that we don't ever wind up surprised by this kind of thing again. We should keep the train moving in the other direction, make sure that treaty works, and make sure that the schedule is expedited.

Senator BAUCUS. That raises two interesting questions. One, the basic point you make, I think, is a good one, namely, since we Americans produce about 30 percent, as I understand, of the offending chlorofluorocarbons, why don't we, as Americans, go much further to reduce or find substitutes.

At the very least, we know that it is questionable whether future CFC production will cause serious ozone depletion at middle latitudes, it is clear that if we find substitutes that we will better off in the long run than if we don't.

What about that, does any panelist disagree with going further, because if we don't, we are taking a big gamble, a big risk?

Dr. MCFARLAND. I would just like to say again that this is very much an international issue. Just to put it in perspective, even if the United States were to completely phase out the use of CFCs, it would be a 30 percent reduction compared to today's.

It would be 30 percent if the rest of the world just kept at today's levels. If some of the rest of the world grew, then it would completely negate that decrease. With the protocol, as it now is written, you have a 50 percent decrease in the emissions of these compounds into the atmosphere over the next ten or twelve years.

Senator BAUCUS. Yes, but if we were to go further, it would be a greater worldwide reduction. The protocol says, later on, by 1999, a 50 percent reduction. If we would go further, the total reduction would even be greater, and we would also exercise a little bit of leadership. We would be showing the world that we are going to go a little bit further. I think that it is good to be a leader here.

One final question, and that goes to resources. Every agency wants more dollars, I understand that. But are there adequate resources committed by the Federal government to specially determine the answers to some of these questions that have to be answered?

Dr. MCELROY. I would comment on that by going back a little bit to a point that Dr. Wilkniss made at the beginning, which has not been repeated, and that is that, when we consider the Antarctic phenomenon, I think that the issue raised in the Antarctic is serious enough to warrant careful attention and whatever curves on release of these chemicals can be implemented, consistent with economic and sociological reality.

But what has not been done so far is to look carefully at the interconnection in the environment. If I could be permitted to speculate on that a little bit, let me do it as follows, drawing the Antarctic ozone problem back to an issue which you, Mr. Chairman, and Senator Chafee, and other members of this committee have dealt with before, namely, the CO_2 climate issue. This is speculation, and I want that to be clear.

In the presence of low ozone over Antarctica, I can speculate that marine productivity in that intensely productive region of the world's oceans in the spring might go down. Given that speculation as an assumption, then the logic continues in a fairly clear way. There would be, under those circumstances, reduced use of nutrients in ocean water that would lead to reduced efficiency of the marine biological pump, and the bottom line is that the ocean would release CO_2.

The ultimate potential for the ocean to release CO_2 is six times larger, according to our present understanding, than the rate at which we dump CO_2 into the atmosphere from fossil fuel.

The conclusion I draw from that, and it goes back to your question, is that it is really very, very important to address the interdisciplinary aspects of earth science as enunciated in the global change type of program. In answer to the question: Are the resouces available to do that as yet? I don't think so.

Senator **Baucus**. Dr. Oppenheimer.

Dr. **Oppenheimer**. I just want to second that and point out that I was astonished by the notion, when Dr. Watson responded, essentially, that this whole question of our future hangs on a very fine tether—whether there are enough people to staff two teams to go to two different places to make the critical measurements.

The fact that there aren't is a reflection of the fact that resources have not gone into these areas of research in the magnitudes that are really required. We ought not to ever be caught in that position again.

Senator **Baucus**. Dr. Anderson.

Dr. **Anderson**. I think, to put this in context, there are three major axes in the scientific problem. There is the question of gas phase processes that Rowland and Molina first suggested in the early 1970s, a major problem, and one that requires intensive research. We are just beginning to address that question.

There are the heterogeneous processes, and then, finally, there is the Antarctic ozone issue. To cover those three areas requires a tremendous input from universities. It requires departments to be reorganized, and deans to become aware of the possibilities.

An answer to your question about resources is easily gleaned by looking at how slow universities are in reorganizing and realizing the global impacts of these problems, and the effect this has on the intellectual environment and faculty staffing. Just as we are very short on staging other field measurements so, too, are we short on the next generation of scientists to support this work.

Senator **Baucus**. Thank you very much.

Dr. Rowland.

Dr. ROWLAND. I have a specific comment, and then a general comment.

The specific comment has to do with my experience in the last couple of years in looking at the ground based ozone data. It would be a real surprise to most of the people involved, the lay people involved, to see how little money has been going into the Dobson Network. We are really dependent upon what amounts to several scientists, total, who are spending their time on making these ground based measurements.

I think that we could easily afford to put $1 million more into that, either by a specific augmentation to the NOAA budget for ground based ozone measurements or by putting more money into NASA, if you want NASA to send it to NOAA.

This is a specific jurisdictional problem in that the ground based measurements are run by the National Oceanic and Atmospheric Administration, and ground based measurements of ozone are not one of their prime concerns. So you either need to direct some money there specifically toward that support, or to arrange that it be covered somewhere else.

Senator BAUCUS. I don't have any further questions. Let me turn to Senator Chafee.

Senator CHAFEE. Did you want to add something, Dr. Rowland?

Dr. ROWLAND. One of the things that is coming out, I think, one of the real advantages of the protocol is that it is turning loose the industrial community toward thinking about substitutes.

When you hear Dr. McFarland talking for the Fluorocarbon Panel, what you are going to get are the substitutes which are similar to fluorocarbons. It is, "How can we maintain control of this market?"

What has happened is different. I take as a specific example McDonald's, which has announced that they are going to replace the plastic they use for keeping hamburgers warm, which now is made with fluorocarbon 11, within the next 18 months. They are obviously not waiting for the development of a substitute chlorofluorocarbon. They are going to go with whatever is on the market now.

I think that this is the big advantage of the protocol. What it has done is to signal to a large number of people in the industrial community that they should be thinking about substitutes, and not just leaving it to the Fluorocarbon Panel people. Now the Protocol has turned it loose for everybody to think about this.

I would like to make one more comment. I come to Washington moderately often. I remember in March and April of 1986 saying that heterogeneous reactions could be very important in the Antarctic ozone, and hearing, "Sheer speculation." Now I don't hear so much "sheer speculation" about the Antarctic ozone hole, and the importance of heterogeneous reactions.

I think what we have to worry about is not nailing absolutely everything down scientifically, because we are too clever to let you nail everything down. We are always going to find a little bit of loophole here, that is the way science works, a little bit of further understanding that we would like to have. But don't wait for us to tell you that it is all nailed down because we will always find something else that requires three more years of work. But I don't think that we need three more years of work to make policy decisions.

Senator **Chafee**. Dr. Rowland, I couldn't agree with you more. I think that this is one of the problems that we are always confronted with. We are meant to make decisions up here based on the best judgment we can, and we can't wait until all the evidence is in because, as you say, it never is in. There is always a little more coming along somewhere.

Is this a fair statement? It seems to me that Dr. Rowland is the only one who has talked about the ground level measurements to any extent, that is, what took place at Arosa, and the other two stations in the United States, Caribou and Bismarck.

Do you attach much to those, Dr. Watson, particularly what the Arosa Station has had over 55 years?

Dr. **Watson**. Yes, I personally believe the ground based stations are essential to get an understanding of what is happening to ozone. It could well be, although I am being premature here, that we will come to a conclusion that ground based stations may be better than the satellite observations for looking for ozone trends. This is going to be a subject that will be debated strongly in two weeks time in Switzerland.

I believe that these findings, which at the moment not many people have seen, from Arosa, Caribou and Bismarck seem to show trends with a seasonal variability, i.e., the largest trends in winter. I think that we have to look at those very carefully and see what they really do mean.

Yes, I believe the observations are very important. Probably in the next two or three weeks, we will start to assess just how important they really are. The observations are quite crucial in my opinion.

Senator **Chafee**. I am repeating myself a little bit, but I am just deeply concerned about all this. In those hearings that Dr. Rowland was mentioning, that we had just about a year ago, you came and testified, and others did also. We want to thank you for that and for the testimony today.

I hope that the alarm does go out from here that this is an area of potential tremendous damage to the world. We, on this committee, wrestle with acid rain, hazardous waste, and solid waste disposal, but I think that this puts all the rest of them in the shadow. This is the only thing that can effect the global climate, that plus the greenhouse effect that you mentioned earlier, Dr. Anderson.

I am delighted that this subcommittee is continuing on this. Clearly, we will pay additional attention to it. Also, I am glad that the chemical manufacturers are getting into finding some substitutes, as was pointed out for McDonald's, and I hope that others will likewise.

I am interested in the comment that was made, I guess you made it, Dr. McElroy, about the lack of students coming along and the expertise being developed. How long has the Department of Earth and Planetary Sciences been going? I suppose that it has been going for quite a while under another name, has it, at Harvard?

Dr. **McElroy**. No. In fact, it is only in its second year. It does, at Harvard, represent an attempt to address the issue that Dr. Anderson mentioned, namely, to bring the expertise of different aspects of the earth under one umbrella.

Senator CHAFEE. Was there a department of astronomy?

Dr. MCELROY. The department of astronomy is separate, but the faculty who came together in the department of earth and planetary science share appointments with biology, physics, applied sciences, and chemistry individually.

Senator CHAFEE. What department are you in, Dr. Anderson? You are at Harvard, too, aren't you?

Dr. ANDERSON. Yes. I am in the department of chemistry in the department of earth and planetary sciences, in the division of applied sciences.

Senator CHAFEE. I would suggest to any young student to jump aboard in the department of earth and planetary sciences. I think that it is the coming thing. Certainly, it is a great opportunity to come down here and testify, I will tell you.

Senator BAUCUS. That is assuming something, Senator.

Senator CHAFEE. Assuming that this is a valuable experience.

Senator BAUCUS. Right.

Senator CHAFEE. I notice that we never pay your way.

I am confident that we will he continuing this oversight, if you would, or interest in this area through the subcommittee.

Senator BAUCUS. That is right.

Thank you, Senator. That was the final point that I was going to make, too, that is, we have had several hearings on this subject. Whenever there is a new experiment or a new expedition, we have a subsequent hearing to analyze the data results and try to determine where we go next. We will continue to do so.

I am interested in this analysis that you mentioned, Dr. Watson, as we get all this data and the rest of the community pour through it. At the appropriate time, we will hold another hearing to see what all this means and where we should go.

Senator CHAFEE. Could we get that schedule once again, Dr. Watson. You said that you are going to Switzerland in a couple of weeks, and then something big was happening in April.

Dr. WATSON. There are two separate schedules. The first one is on Antarctic ozone, and where do we go from here. We will have a series of small science teams trying to understand what went on in Antarctica this year. We would then have one large workshop in February, and plan to have preprints available to everybody by March or April of next year on the results of Antarctic ozone. That we would hope, and we would believe, that the scientists who went to McMurdo this year would work on a very similar schedule.

By April of next year, most of the data that was taken this year on Antarctic ozone should be analyzed and available for public consumption.

Secondly, though, there has been this on-going panel, an international panel that I am chairing, to try and look at trends in ozone temperature, other trace gases, and cause and effect. It was stimulated by the observations of Don Heath using NASA satellite data that there had been a 7 percent change in ozone since 1979.

That particular panel, the steering committee of that panel, plus some outside reviewers from Europe predominently, will meet in Switzerland in two weeks time to try and evaluate: Is the satellite data good? Is the ground based station data good? What are the causes and effects of ozone changes primarily since 1979? But also the analysis will go back to the early/mid-1950s and analyze the record completely, looking at whether the nuclear bomb tests had any effects in the early 1960s.

We will have our meeting in two weeks time in Switzerland. We will have our report ready, in final form, we would hope, by about January 1. It will be in final form, but it won't be nicely printed then, but we will be able to give you a copy of that. It will be a long report, so we will have an executive summary that is a little bit more readable.

Senator CHAFEE. There is just one final thing that I would like to say.

Mr. Chairman, I think that we do want to acknowledge the Chemical Manufacturers Association. I have found in working on this problem for a couple of years now that they have been responsive and concerned. This is not to suggest that we always agree with them, but I think that has been an unusually responsible organization. I think that we ought to acknowledge it from this platform.

Dr. McFARLAND. Thank you.

Senator BAUCUS. Thank you very much, everyone. We will be continuing this, and your contributions have been very helpful.

The hearing is adjourned.

[Whereupon, at 12:27 p.m., the subcommittee recessed, subject to the call of the Chair.]

[Statements submitted for the record follow:]

Statement of Dr. Peter E. Wilkniss
Director, Division of Polar Programs
National Science Foundation Before a Joint
Hearing of the Subcommittees on Hazardous Waste and
Toxic Substances, and Environmental Protection of the
Committee on Environment and Public Works
United States Senate on October 27, 1987

Mr. Chairman, I am pleased to have the opportunity to discuss with you the role of the U.S. Antarctic Program in research on stratospheric ozone depletion in the Antarctic. Since the early 1970's the National Science Foundation, with vital Congressional support, has budgeted for and managed the U.S. Antarctic Program. The program provides research support and an infrastructure of permanent stations, temporary field camps, a heavy airlift capability of a Navy squadron operating NSF ski-equipped C-130 aircraft, Coast Guard icebreakers, and helicopter and ship support.

The continuing and substantial investment in the Antarctic Program provides for U.S. presence in Antarctica and research in the atmospheric, earth, ocean, and biological sciences. It was this long term commitment to a continuing Antarctic Program and presence that made possible the deployment in August 1986 of the first National Ozone Expedition (NOZE-I) to McMurdo Station, located at 78°South, about 2200 miles directly south of Christchurch, New Zealand.

NOZE-I followed the British announcement of discovery of the ozone hole by a little over a year. The expedition was made up of four teams of researchers from the NOAA Aeronomy Laboratory, Boulder, Colorado; the Jet Propulsion Laboratory, Pasadena; the University of Wyoming, and SUNY Stony Brook.

Funding was provided by NOAA, NASA, NSF and the Chemical Manufacturers Association. This is a good example of how Government agencies can pull together in a crisis situation.

On their return from Antarctica, NOZE-I scientists announced preliminary findings. They found that dynamic processes play an essential role in the ozone hole phenomenon by producing unusual springtime conditions of the antarctic atmosphere and by causing the hole's seasonal disappearance. However, they thought that a chemical mechanism is fundamentally responsible for the formation of the hole. These conclusions resulted from ground-based and balloon observations.

The existing U.S. base at McMurdo and winter aircraft access to it, as well as the support of Navy and contractor personnel involved in the U.S. Antarctic Program, were prerequisites to the success of NOZE-I.

This year's NOZE-II built on NOZE-I in several ways. A core of NOZE-I investigators emerged from the NOZE-II competitive selection process, and August flights to McMurdo again were used. Instrumentation, however, was significantly improved during the time between the two deployments to allow better and expanded data collection. A totally new approach was the use of LIDARS to probe the Antarctic atmosphere with laser beams.

In addition to continuity, there were major new approaches, particularly observations from NASA aircraft staged from Chile. Also, the Antarctic Program's ice strengthened research vessel, Polar Duke, brought a NASA group to Palmer Station, located on an island just off the Antarctic Peninsula at

64° South. From Palmer, they have been flying a series of ozonesonde balloons. Another new element is the initial study of biological effects of the increased ultraviolet radiation reaching the Earth's surface as a result of the ozone hole. In one of the biological studies, researchers from Texas A&M University will undertake the first quantitative assessment of the effects of ultraviolet radiation on antarctic phytoplankton—the microscopic, single-celled plant organisms that constitute the base of the antarctic food web, feeding the small fish, mollusks, and crustaceans, such as the shrimp-like krill, on which penguins and some whales depend for sustenance. Because the phytoplankton is thought to be very sensitive to ultraviolet radiation, effects on marine animal life could be far reaching. In a second study, a researcher from the University of California, San Francisco will conduct experiments on the ability of organisms to repair genetic damage caused by exposure to ultraviolet radiation. DNA molecules that carry the genetic code for cells will be examined both with respect to damage of the DNA and effectiveness of repair mechanisms. If repair does not take place, there will be mutations affecting future generations of single cell organisms and larger plants and animals. Both biological projects involve field work at Palmer Station in November 1987 through January 1988.

The work of the six teams at McMurdo this year indicates a substantially larger than expected ozone decline and also strengthens the chemical theory of ozone depletion that was a central NOZE-I discovery. The work verifies that the region of the ozone hole is subject to highly unusual atmospheric chemistry. The data collected beginning in late August show a dramatic depletion of ozone at an altitude of about 9 miles (15km, 50,000 ft.). This phenomenon was associated with levels of chlorine monoxide more than 100 times greater than normally found in the lower stratosphere. The chlorine monoxide is an ozone killer that is produced mainly from chlorofluorocarbons. The appearance of the ozone hole over Antarctica may be related to chemical reactions that occur on the surface of ice crystals that make up the polar stratospheric clouds. The depletion phenomenon disappears as the polar atmospheric vortex breaks down, the austral summer approaches, the clouds with associated trace gases are dispersed and stratospheric ozone from elsewhere in the southern hemisphere replaces that which has been destroyed.

A NOZE-III expedition has been announced with proposals due to NSF in January of 1988. It is expected to include further atmospheric chemistry and biological effects studies. But beyond this, where should atmospheric ozone research in Antarctica go? We see a series of needs involving logistics as well as science that will enhance capabilities to understand the ozone problem as well as other antarctic phenomena with global significance. These needs include:

Year Round Access to Antarctica

NOZE-II has demonstrated vividly that, despite excellent results, the very onset of the ozone hole can only be ascertained by deep winter access (July/early August) to the Continent. Therefore, a major initiative has been started to provide ground based air traffic control, navigation and visual aids, skiway preparation and aircraft internal landing approach systems to achieve this arduous, and potentially dangerous, task efficiently and safely. Similar considerations apply to access by ship through winter ice. The present ship Polar Duke was pressed to its limits to transport a

NOZE-II group to Palmer Station in late July/early August this year. The new ship requested in the FY 1988 budget would be fully capable of meeting this need. In addition to NOZE, biological research, and climate and sea-ice research all require year-round access to the south polar area provided by the ship included in the FY 1988 budget.

Special Antarctic Research Facilities

There is great difficulty in carrying out research of this delicate nature when dealing with antiquated laboratories, exposure of research equipment to the pervasive wind blown volcanic dust prevalent at McMurdo. Funding was included in the FY 1988 budget to construct a special building that will house state-of-art equipment and allow research to be conducted in a safe, clean environment, that is not affected by other activities.

Long Term Impact on Biomass

The ozone hole is now evident over the tip of South America. A conjugate program is needed in Antarctica/South America, to monitor the impact the ozone hole is having on animals and on the entire biomass. A joint program with South American and other countries is being planned.

Other Logistics Requirements for Year Round NOZE Activities

Facilities at the South Pole are needed to enhance year-round monitoring of ozone depletion and related measurements.

Special facilities to carry out balloon operations at McMurdo, South Pole and on board the new ship, are needed to fully understand the structure of the ozone depletion process.

Enhanced direct read-out from weather and communications satellites at U.S. Antarctic stations, is required to allow expeditious computer manipulation of meteorological data and improvements in weather forecasting for operational needs, especially year round access to the continent.

In summary, the United States Antarctic Program requirements in connection with ozone research pose new challenges and are supported by the President's FY 1988 budget. These activities require the full FY 1988 request, especially in view of needs which could not be foreseen in the extremely fast moving events in Antarctic research and operations.

STATEMENT OF

DR. ROBERT T. WATSON

EARTH SCIENCE AND APPLICATIONS DIVISION

OFFICE OF SPACE SCIENCE AND APPLICATIONS

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

BEFORE THE

SUBCOMMITTEE ON HAZARDOUS WASTES AND TOXIC SUBSTANCES

SUBCOMMITTEE ON ENVIRONMENTAL PROTECTION

COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS

U. S. SENATE

Mr. Chairmen and Members of the Subcommittees:

I am pleased to be here today to discuss our current understanding of the cause or causes of the observed decrease in ozone over Antarctica during springtime since the late 1970's.

In my testimony today, I will speak on behalf of the scientists and team who participated in the Airborne Antarctic Ozone Experiment, using as a basis the statement of findings prepared by the science team in Punta Arenas, Chile. Before doing so, however, I would like to stress that the tremendous success of this mission is the direct result of the outstanding cooperation and effort of the large and diverse group of participants in this intense and challenging campaign. The success of the mission has exceeded any of our prior expectations, and for this credit must go to not only the scientists, but to the flight, ground and support teams associated with the project.

This scientific summary statement was prepared by the scientists who went to Punta Arenas, Chile to study the Antarctic ozone hole. This summary represents the views of the scientists themselves and not necessarily those of the cosponsoring organizations. The findings that will be presented are preliminary. Under normal circumstances, scientists studying such a complex scientific issue would take many months to years to disclose their initial findings. However, the issue of ozone perturbation is one of justifiable public concern, and hence the public should be kept abreast of the current scientific thinking. It is in this spirit that we would like to share our provisional picture of the Antarctic springtime ozone hole. Furthermore, this will help to stimulate the scientific inquiry and debate that can only lead to an improved and timely understanding of the phenomenon. A much more complete and final interpretation of our findings will be forthcoming after a planned intensive series of scientific meetings and the submittal of a group of scientific papers to the peer review process. This procedure will occur within the next six months.

Description of Goals and Objectives of the Mission

Three basic theories have been proposed to explain the observed decrease in spring-time Antarctic ozone that has been occurring since the late-1970's. One class of theories suggest that the hole is caused by the human activity of loading the atmosphere with chlorinated and brominated chemicals. Chlorofluorocarbons (CFC's) and Halons are contributing increasing levels of chlorine and bromine to the atmosphere. These compounds could then efficiently destroy stratospheric ozone in the Antarctic environment because of the special geophysical conditions that exist in this region of the atmosphere, i.e. a contained polar vortex (an isolated air mass), cold temperatures, and the presence of polar stratospheric clouds. A second class of theories suggests that there have been changes in the circulation of the atmosphere, which now transports ozone-poor air into Antarctica. A third theory postulates solar and cosmic ray induced, periodically enhanced abundances of oxides of nitrogen, which can cyclically destroy ozone.

The NSF-coordinated expedition to the McMurdo station in Antarctica last year was exceptionally successful in increasing our understanding of the Antarctic ozone hole. In conjunction with other experiments, this ground based effort demonstrated the recurrence of the ozone hole, the altitude over which ozone was depleted, that chlorine and nitrogen chemistry was highly perturbed relative to that observed at mid-latitudes, and that the solar cycle theory is an unlikely explanation. However, the McMurdo data were insufficient to distinguish adequately between the relative contributions of the first two classes of theories. Therefore, the goal of the present airborne campaign is to improve our understanding of the relative contributions of these, and possibly other, mechanisms to the formation of the Antarctic ozone hole.

One of the key environmental issues is whether the ozone depletion observed in Antarctica will always be localized in and around Antarctica, or whether it is a precursor of future global changes. A longer term objective of this campaign is to be able to provide information relevant to answering this question.

Participants, Sponsors, and Foreign Government Support

The campaign was coordinated by the National Aeronautics and Space Administration (NASA) and cosponsored by NASA, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the Chemical Manufacturers Association (CMA). In addition, the British Meteorological Office (BMO) and the European Center for Midrange Weather Forcasting (ECMWF) provided significant contributions to the project.

Scientists, engineers, and other personnel from Harvard University, University of Denver, University of Washington, University of Colorado, National Center for Atmospheric Research, Jet Propulsion Laboratory, NASA Ames Research Center, NASA Langley Research Center, NASA Goddard Space Flight Center, NOAA Aeronomy Laboratory, the British Meteorological Office, the European Center for Medium Range Weather Forecasts (ECMWF), Centre Nationale Recherches Meteorologiques, and Atmospheric and Environmental Research, Inc. participated in this campaign. Dr. J. C. Farman of the British Antarctic Survey kindly made available Halley Bay ozonesonde data. Scientists from both Chile and Argentina were also involved.

Key participants in this campaign were also the flight and ground crews of NASA, Lockheed Corporation, and Northrop Corporation, who flew and maintained the ER-2 and DC-8 research aircraft under very challenging conditions. Research and Data Systems, Corp. provided the necessary telecommunication links and support.

The Chilean government hosted the airborne campaign, which was based out of Punta Arenas. The Chilean Air Force supplied the facilities and logistical support. The Chilean Antarctic Institute provided advice regarding the study area. In addition, invaluable assistance was provided by the Direccion General De Aeronautica Civil, and the National Meteorologic Service of Chile.

Other countries also helped: Panama, Costa Rica, Peru, and Ecuador cooperated with the overflights necessary for the transit from the United States to Chile. The government of Argentina offered alternate landing fields for the aircraft as they returned from their Antarctic missions. The National Meteorological Service of Argentina furnished data from Marambio. Lastly, the government of New Zealand assisted with the transcontinental Antarctic flight by the DC-8 that was part of the return to the United States.

Description of Campaign

The Airborne Antarctic Ozone Campaign succeeded in making 12 flights of the high altitude ER-2 aircraft, and 13 flights of the DC-8 medium altitude aircraft over Antarctica. The ER-2 typically operated at geometric altitudes relative to sea level between 12.0 and 18.7 km and flew to 72 degrees South along the Palmer Peninsula. The DC-8 operated at altitudes up to about 10 km and with its long range capability was able to reach the South Pole on several occasions, and returned to the United States via New Zealand after crossing the Antarctic continent. The project had available to it Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) images of the total ozone column of the southern hemisphere within a day of observation and of the orbits passing over the region of the Antarctic peninsula within 2 to 4 hours of observation. Aerosol and cloud extinction data were also available from the Nimbus-7 Stratospheric Aerosol Measurement (SAM II) and Stratospheric Aerosol and Gas Experiment (SAGE II) on the Earth Radiation Budget Satellite. The latter also provided ozone measurements. Twice daily analyses and forecasts of winds and temperatures up to 30 mb, 22 km, for three days ahead, were provided by the BMO in chart form, plus forecasts of the trajectories of air parcels on surfaces along which air masses move. Photochemical modelling along these trajectories was done using the aircraft observations. The ECMWF provided once a day analyses and forecasts up to 30 mb for 10 days ahead. A small theory team assisted the experimental scientists with the interpretation on a day to day basis. This approach was possible because of the availability of rapid data reduction facilities and an extensive, dedicated international telecommunications network.

Detailed lists of the participants, a discussion of the theories being addressed, the approach taken in the tests of these theories, and a description of the apparatus involved are given in the Airborne Antarctic Ozone Experiment Plan (NASA and NOAA, July 1987). Copies are available on request from NASA Ames Research Center or NASA Headquarters.

Data obtained from the ER-2 and DC-8 instrumentation

The spatial and temporal distribution of a large number of relatively short-lived chemical constituents that participate in chemical reactions that affect the abundance of ozone were measured from both the ER-2 and DC-8. Instruments aboard the ER-2 resulted in measurements of the distributions of ozone (O_3), chlorine monoxide radical (ClO), bromine monoxide radical (BrO), total odd nitrogen (NO_y), nitric oxide (NO), and water (H_2O) in the vicinity of the aircraft at altitudes ranging from 12 to 18 km above the Earth's surface, well into the altitude region where ozone is undergoing depletion. Instruments aboard the DC-8 measured the abundances of H_2O and O_3 in the vicinity of the aircraft, the vertical distribution of O_3 for approximately 10 km above the aircraft, and the total column amounts of O_3, hydrochloric acid (HCl), chlorine nitrate ($ClONO_2$), chlorine dioxide (OClO), BrO, hydrofluoric acid (HF), NO, nitrogen dioxide (NO_2), nitric acid (HNO_3), as well as a number of other constituents, above the aircraft altitude.

Additionally, the temporal and spatial distributions of long-lived chemical tracers and dynamical variables were measured in order to understand atmospheric motions. These included measurements of nitrous oxide (N_2O), methane (CH_4), chlorofluorocarbons 11 ($CFCl_3$) and 12 (CF_2Cl_2), carbon tetrachloride (CCl_4), and methylchloroform (CH_3CCl_3). In-situ measurements of all of these species were made from both the ER-2 and DC-8, and column measurements of most from the DC-8. The size distribution, abundance, and composition of particles was determined by instrumentation aboard the ER-2, as well as the vertical distribution of aerosols from 12 to 28 km by the DC-8 lidar, in an effort to understand the role of heterogeneous processes. Additionally, atmospheric pressure, temperature, lapse rate, and winds were measured aboard the ER-2 to determine the state variables and dynamical structure of the atmosphere.

The project had regular ozone sonde data available from the Palmer station, the Halley Bay station, the South Pole station, and McMurdo. These define the vertical distribution of ozone at points not routinely covered by the flight tracks. Ozonesondes were launched at special times from Palmer and the South Pole to coincide with aircraft overflights of those locations.

The analyses of some of these data sets have not yet been completed, either because of the lengthy data reduction procedures required or because of the sheer volume of raw data acquired. An example of the latter is the meteorological data set, whose initial analyses had the primary goal of forecasting the flight conditions. Furthermore, many of the analyses of the chemical data sets are clearly only preliminary, to be refined by recalibration checks and more sophisticated re-analyses available at the home laboratories. As a consequence, the initial picture summarized below cannot be a balanced, complete, and final one.

Results and their relationship to theories

The processes controlling the abundance and distribution of ozone in Antarctica are complex and intertwined. However, given the successful nature of this campaign, we are now in a position to start to more fully appreciate the exquisite balance between the meteorological motions and the photochemistry. We will present our preliminary scientific findings as answers to a series of posed scientific questions that are relevant to public policy.

1) Did the springtime ozone hole occur over Antarctica in 1987?

Yes. TOMS satellite, balloon ozonesonde, and both ER-2 and DC-8 aircraft measurements of ozone showed that the springtime ozone decrease occurred again this year. TOMS showed the spatial extent of the phenomenon is continental or greater in scale and revealed the temporal change in the total column of ozone. The abundance of ozone in August and September of 1987 was lower than any previous year at all latitudes south of 60 degrees. In mid-September of this year column ozone was approximately 15% lower at both 70 and 80 degrees south than the values observed in the lowest previous year of 1985. The balloon-sonde data demonstrated that ozone was depleted in the altitude region between approximately 13 and 24 km at Halley Bay, and 15 and 24 km at Palmer. Ozone trends observed at Halley Bay and at Palmer are quite similar, with an approximate 50% decrease observed from mid-August to mid-September near 18 km. The upward looking lidar aboard the DC-8 observed more than a 50% decrease in O_3 at 77 to 90 degrees south between 14 and 19 km, during September, but no discernible trend between 12 and 14 km. There was also evidence from the lidar data of a decrease in O_3 up to 23 km. The in-situ ER-2 instruments observed changes consistent with this picture.

The TOMS data showed that ozone did not simply change monotonically with time, but in some instances changed dramatically over large spatial scales in the matter of only a day or so. One example of such a rapid change in ozone is demonstrated by the TOMS data for September 4-6 over the Palmer Peninsula and Weddell Sea. Changes of greater than 25 Dobson units (DU) in one day were observed over large regions (3 million square km). The ozone sonde data from Halley Bay and the DC-8 lidar data showed that, during this event, the ozone was depleted over a wide altitude range, from about 14 to 23 km.

2) Does the evidence indicate that both chemical and meteorological processes are responsible for the ozone hole?

The weight of observational evidence strongly suggests that both chemical and meteorological mechanisms perturbed the ozone. Additionally, it is clear that meteorology sets up the special conditions required for the perturbed chemistry.

3) Was the chemical composition of the Antarctic stratosphere observed to be perturbed?

Yes. It is quite evident that the chemical composition of the Antarctic stratosphere is highly perturbed compared to predictions based on currently accepted chemical and dynamical theories. The present findings are consistent with the observations made last year from McMurdo. The distribution of chlorine species is significantly different from that observed at mid-latitudes, as is the abundance and distribution of nitrogen species. The amount of total water within some regions of the vortex is significantly lower than anticipated.

Since late August the abundance of the chlorine monoxide radical within the polar chemically perturbed region has been elevated by a factor of more than 100 relative to that measured at mid-latitudes at the highest altitude at which the ER-2 was flown, about 18.5 km. However, the abundance of ClO was observed to decrease rapidly towards lower altitudes. At the highest flight levels, the abundance of ClO at local solar noon ranged between 0.5 and 1 ppbv for the last month of the campaign. While we have no data at higher altitudes, the observed increase in the abundance of ClO from lower altitudes, coupled with the observed low column abundances of HCl, suggests that the ClO abundance may increase somewhat at altitudes above 18 km. In addition to the steep decrease in ClO abundance at lower altitude, the abundance of ClO was also observed to decrease dramatically outside of the chemically perturbed region.

Chlorine dioxide, OClO, which is most likely formed in a reaction sequence involving the ClO radical, was observed both day and night at highly elevated concentrations compared to those at mid-latitude. The preliminary analyses of these observations are consistent with measurements made from McMurdo last year. The column content of hydrochloric acid, HCl, which is one of the major chlorine reservoirs at mid-latitudes, is very low within the chemically perturbed region reaching column contents below 1×10^{15} molecules per cm^2. In addition, the column amount ratio of HCl/HF within the chemically perturbed region decreased significantly from a normal mid-latitude value of 4 to a value less than unity. While chlorine nitrate was observed, the data have yet to be fully analyzed thus precluding a statement at this time about its abundance.

The bromine monoxide radical has been observed at concentrations of a few pptv within the chemically perturbed region of the vortex at the flight levels of the ER-2. The abundance of BrO decreases at lower altitudes. However, because the observed concentrations are close to the detection limit of the instrument, little more can be said about the altitude dependence. The low measured abundances of BrO, coupled with our current lack of understanding of the ClO + BrO reaction means that we cannot currently assess the significance of this mechanism for ozone reductions at the ER-2 flight levels.

The ER-2 observations of the abundance of odd nitrogen, which is the sum of all nitrogen-containing reservoir and radical species, show, like total water, very low values within the chemically perturbed region of the vortex , indicating that the atmosphere has been denitrified, as well as dehydrated. Abundances of NO_y of 8-12 ppbv were observed outside the chemically perturbed region, while abundances of 0.5 to 4 ppbv were observed inside the chemically perturbed region. A similar large change was observed for one of the nitrogen components, i.e. nitric oxide, NO. In addition, some of the NO_y observations suggest that NO_y component species are incorporated into polar stratospheric cloud (PSC) particles and nitrate was observed in the particle phase on some of the filter samples and on some of the wire impactor samples taken in the chemically perturbed region of the vortex. The column measurements of nitric oxide, nitrogen dioxide, and nitric acid made from the DC-8 exhibit a strong decrease in the abundance of these species towards the center of the vortex. These low values of nitrogen species are contrary to all theories requiring elevated levels of nitrogen oxides, such as the the proposed solar cycle theory.

4) How do the observed elevated ClO abundances support a chemical role in the formation of the ozone hole?

There is no longer debate as to whether ClO exists within the chemically perturbed region near 18 km at abundances sufficient to destroy ozone if our current understanding of the chlorine-ozone catalytic cycle is correct. The rate of decrease in ozone during the month of September at the highest altitudes at which the ER-2 was operated during this campaign is consistent with simultaneously observed concentrations of ClO. However, our present understanding of key chemical reaction rates and photodissociation products within the catalytic process is incomplete. Thus, laboratory studies are urgently needed. It is essential to define the rate of ClO dimer (Cl_2O_2) formation and the photolysis products of dimer decomposition because only one of several possible routes leads to ozone destruction. Once the results of ongoing laboratory studies become available, these in-situ ClO data will allow the chemical mechanism to be quantitatively defined and its consequences better understood.

There is another line of observational evidence consistent with ozone destruction by chlorine catalysis. In the month of August, a consistent positive correlation between ClO and O_3 was observed. By the middle of September, as the ozone concentration was dropping at ER-2 altitudes, a strong anti-correlation developed between ClO and O_3. The anti-correlation was usually present on both large and small scales within the chemically perturbed region.

There are observations that are not entirely consistent with these chemical arguments. For example, based on preliminary data from this year and data from last year from McMurdo, the observed diurnal behavior of OClO, is difficult to rationalize with the present chemical mechanisms, particularly in light of the new observations that the abundances of BrO are low at ER-2 flight altitudes.

5) Can the elevated abundances of ClO inside the chemically perturbed region of the vortex be explained?

Significant progress was made. Observational data that air within the chemically perturbed region of the vortex is dehydrated and that the NO_y abundances are very low are consistent with theories that have been invoked whereby the chlorine reservoir species, $ClONO_2$ and HCl, can react on the surfaces of polar stratospheric clouds to enhance the abundance of active chlorine species, i.e. ClO. The observations also support the picture that the abundance of NO_y is low because odd nitrogen can be removed from the atmosphere by being tied up in ice crystals, which can then gravitationally settle to much lower altitudes. Low abundances of NO_y are needed to prevent the rapid reconversion of ClO to $ClONO_2$. This picture is further supported by the observations of low column abundances of HCl, by occasional observations of high levels of nitrate found in the ice particles, and by the visual and lidar observations of high cirrus and polar stratospheric clouds.

One observation which is currently difficult to understand is the sharp decrease in the abundance of ClO at lower altitudes. This could be due to a lack of understanding of either the abundance or partitioning of ClO_y, or to dynamical effects. Lack of observations of reactive hydrogen containing radicals, hydroxyl (OH) and hydroperoxy (HO_2) currently prevents an assessment of their role in the conversion of chlorine reservoir species to ClO.

6) How do the observations support a meteorological role in the formation of the ozone hole?

There were instances of rapid large scale changes in total ozone where meteorology appears to have been the controlling factor. One such event occurred over the Palmer Peninsula on September 5. Over a period of 24 hours total ozone as observed by TOMS decreased by 25 DU to below 200 DU over an area of about 3 million square km. Such a rapid decrease is difficult to explain chemically. The origin of that air is not known. It could be either air naturally low in ozone, tropospheric/lower stratospheric, or air in which ozone had been chemically depleted. The feature moved over the Weddell Sea and persisted until September 16, when it merged with two other regions of low total ozone. Lidar measurements from the DC-8 showed low ozone values and extensive aerosol layers between 14 and 19 km in the region of the TOMS minimum of ozone. This and other similar events evident in the TOMS ozone data and the SAM II PSC data between September 5 and 14 were spatially correlated with deepening surface pressure lows with marked meridional flow from middle to high latitudes at lower stratospheric levels. The detailed meteorological mechanism by which the surface lows produce the low column ozone remains unclear and further analysis is required.

The data offer no support for sustained large scale upwelling. In the restricted region covered by the ER-2, 54 to 72 degrees south latitude and from altitudes of 12.5 to 18.5 km, measurements of CFC-11 and N_2O which act as tracers of air motions show no evidence of a general increase in abundances above about 14 km during the mission, although there were instances of structure and elevated values.

The meteorology must play a role in the dehydration and denitrification processes. It is crucial to understand whether the necessary low temperatures are maintained radiatively or by ascent, or some combination of both.

7) Does the complexity of the situation suggest that we need to understand the interplay between meteorology and chemistry?

Yes. It is clear from our ER-2 flights that the region of dehydrated and denitrified air maintained a sharply defined latitude gradient throughout most of the campaign. On a purely meteorological definition, the vortex edge would be well outside the dehydrated, denitrified region. The meteorological flow must therefore have been such as to maintain a kind of "containment vessel", in which the perturbed chemistry could proceed without being influenced by mixing in more normal stratospheric air from outside or below.

Very low values of CFC-11, CFC-12, CH_3CCl_3, and N_2O were observed at the upper levels of the ER-2 flight track within the "containment vessel". A key question is how these low values are produced and maintained in the chemically perturbed region.

The concept of mixing at the region of sharp latitudinal gradient is important, since it has the potential to supply nitrogen oxides which would tend to decelerate the chlorine chemistry. The meteorology is thus important in the termination phase as well as in the initiation phase.

8) Can we quantitatively separate the contributions of chemistry and meteorology to the formation of the ozone hole?

No. The September 5 event illustrates the complexity of the ozone hole, and the difficulty of deriving unambiguous dynamical or chemical signatures. The magnitude and rapidity of the decrease are difficult to ascribe to a chemical cause. Air of low ozone content appears to have been transported into the region. The origin of that air is not known. It could be either air naturally low in ozone, tropospheric/lower stratospheric, or air in which ozone had been chemically depleted.

Another illustration of the difficulty of clearly establishing chemical or dynamical mechanisms is the decreasing trends in ozone in regions of low ClO outside of the vortex whose magnitudes are comparable to those within the vortex. This is evident from an examination of the ozonesonde data from the Palmer station at 64 °S and comparing it to the Halley Bay data at 78 °S, and the DC-8 lidar data. In addition, downward trends of ozone were observed in the lower altitude region where ClO concentrations were substantially lower than at 18 km.

9) What are the global implications of the Antarctic ozone hole?

Until we better understand the cause or causes of the spring-time Antarctic hole, we will not be able to address this key question in a responsible manner. Thus, at this time, it is premature for us to speculate on this important topic. However, as we continue to analyze the data that we have acquired and further test and expand the pictures that we have developed, we will be in a better position to address this important question.

10) When will the data be in a form suitable for use in formulating national and international regulatory policies?

As noted in the opening paragraph, the schedule for the assimilation and publication of the results is brisk. Peer reviewed publications will appear in 1988. The results from the 1987 ground-based McMurdo campaign will likely appear on about the same schedule. Both sets of these completed conclusions would be the best basis for any possible policy re-evaluations. The major international scientific review scheduled for 1989, which will serve as input to the 1990 policy review of the Montreal Protocol, will have these conclusions available.

Senate Testimony

Presented by

Professor James G. Anderson

Department of Chemistry

Harvard University

27 October 1987

Before the

Combined Subcommittees

on

Environmental Protection

and

Hazardous Waste and Toxic Substances

My name is James G. Anderson. I am a faculty member of Harvard University and a principal investigator on the recent Airborne Antarctic Ozone Experiment described in the previous testimony. Time restrictions on this testimony require severe distillation of our results. I will confine my comments to the results from the NASA ER-2 aircraft. The primary objective of our work on this mission was to establish the concentration, distribution and temporal evolution of ClO using this high altitude (18.5 km) observation platform. The ClO radical is the central constituent in the scientific case linking surface release of CFCs to ozone destruction in the Antarctic polar vortex. The instrument also detected BrO and was part of a complement of instruments aboard the ER-2 to detect ozone, water vapor, nitrogen oxides, nitrous oxide, fluorocarbons and other tracer gases using whole air samples, condensation nucleii, aerosols, pressure, temperature and winds.

This testimony will emphasize results from the recent Antarctic mission with particular emphasis on the scientific case linking chlorine compounds within the vortex to erosion of ozone within the same region. The central question we address is straightforward: Are chlorine compounds (and thus CFCs) responsible for the destruction of O_3 in the Antarctic vortex?

Two points, which appear almost daily in the nation's newspapers, are critical. First, if chlorine compounds destroy ozone at rates high enough to explain the "ozone hole", then they do so via catalytic cycles. That is, chlorine acts as a chaperone accelerating the conversion of ozone to molecular oxygen. Second, if these catalytic cycles operate then they are rate controlled by a single species — the ClO free radical. For this the ClO radical has become a household word.

Progress in science is achieved when cause and effect are isolated. This fact underlines the unique contribution made by the Airborne Antarctic Ozone Experiment — that mission asked and in large measure answered two questions which had been beyond our grasp:

1. Can dynamical (i.e., meteorological) and chemical processes be separated to uniquely define a chemical component to the observed destruction of ozone? Specifically, can a chemical containment vessel (a 'beaker') be identified which maintains its integrity from the end of polar winter through the period of major ozone loss? Is there a region of the polar vortex that remains isolated from external intrusion such that processes taking place within the vortex are strictly chemical rather than meteorological in origin?
2. Within this chemical containment vessel, is the ClO radical concentration sufficiently high to remove O_3 at the observed rate?

This sets the stage. If the answer to both questions is yes, then the following events must take place: Within the containment vessel over the Antarctic, ozone would survive the polar night unperturbed and ClO would increase dramatically in concentration as sunlight returned. ClO would reach levels adequate to remove O_3 in three to four weeks within the chemical containment vessel and O_3 would erode at a predictable rate dependent on the ClO concentration in the same region of the atmosphere. This would leave diminished ozone levels high in ClO within the containment vessel.

What did the Airborne Antarctic Ozone Experiment find?

Twelve flights of the ER-2 aircraft were completed into the vortex region. A series of simultaneous *in situ* observations defined a region within the vortex above an altitude of 17 km which remained free from external intrusion throughout the six week period of the mission beginning 17 August 1987. Whole air samples (NCAR/NASA Ames Research Center, L. Heidt and J. Vedder, Principal Investigators) reported concentrations of CFCs, CH_4 and N_2O with a spatial resolution of ~ 1 km in conjunction with high resolution data on N_2O (Ames Research Center, M. Lowenstein and J. Podolski, Principal Investigators) which demonstrated the absence of horizontal and upward intrusion of air into the vortex above 17 km. *In situ* measurements of H_2O (NOAA Aeronomy Lab, K. Kelly, Principal Investigator), nitrogen oxides (NOAA Aeronomy Lab, D. Fahey, Principal Investigator), ozone (two instruments: NASA Ames, W. Starr, Principal Investigator, and NOAA Aeronomy Lab, M. Proffitt, Principal Investigator) and ClO clearly defined a desiccated, denitrified region within which free radical concentrations were elevated.

The amount (the "mixing ratio") of ClO was found to exhibit a striking increase as the aircraft passed through the wall of the chemical containment vessel, increasing by X10 within a few tens of horizontal kilometers. On 17 August, the first flight, the ozone concentration was approximately 2.5 ppm, and showed no significant change in concentration between the region outside and inside the containment vessel. Within the vessel there was a positive correlation between ClO and O_3. On 17 August, the ClO mixing ratio reached 0.1 parts per billion within the containment vessel, approximately fifty times midlatitude concentrations. By 23 August, the ClO mixing ratio reached 0.5 ppb within the vessel, 250 times normal concentrations. On the 23rd, the ozone mixing ratio still exhibited little contrast between the regions inside and outside the vortex which were both comparable to unperturbed levels emerging from the polar night.

Through the last week of August and into the first week of September, the peak ClO concentrations observed within the chemical containment vessel increased such that by 9 September, ClO mixing ratios had reached 0.7 ppb or nearly 400 times normal levels. The morphology (the shape) of the ClO distribution remained in large measure unchanged — outside the containment vessel ClO was variable between 5 and 30 ppt, increasing by X10 through a very small horizontal displacement and then increased more slowly to define a "dome" of highly amplified ClO within the containment vessel.

By 16 September, a dramatic anticorrelation between ClO and O_3 had developed such that as the aircraft passed through the chemical containment vessel wall, O_3 dropped by nearly a factor of three precisely where ClO increased by a factor of ten. The negative correlation (high ClO concentration - low ozone concentration) was apparent on both the large scale (i.e., inside and outside the vortex) and the small scale (fluctuations in O_3 and ClO over horizontal scales of 1 km).

Finally, an analysis of the rate of disappearance of ozone at peak aircraft altitudes (18.5 km) when compared with the measured amount of ClO in the same air mass demonstrate that the predicted destruction rate of O_3 by the major catalytic cycle (ClO dimerization followed by photodissocation to Cl + ClOO proposed by Molina) matches the observed loss rate of ozone within experimental uncertainty.

In conclusion, within a clearly defined chemical containment vessel inside the Antarctic polar vortex, ClO exists at concentrations reaching 500 times that of the normal atmosphere. Cause and effect linking the existence of chlorine in the atmosphere (and thus the release of CFCs at the surface) to the destruction of ozone in the atmosphere has been established. While key issues regarding the specific mechanisms remain, the clarity of the data exceed that of many laboratory experiments. The amount of ozone destroyed each year by the Antarctic phenomena is potentially of considerable global significance.

CMA

CHEMICAL MANUFACTURERS ASSOCIATION

WRITTEN STATEMENT

OF

DR. MACK McFARLAND

ON BEHALF OF THE

FLUOROCARBON PROGRAM PANEL

OF THE

CHEMICAL MANUFACTURERS ASSOCIATION

TO THE

ENVIRONMENTAL PROTECTION

AND

HAZARDOUS WASTES AND TOXIC SUBSTANCES
SUBCOMMITTEES

OF THE

COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS

UNITED STATES SENATE

OCTOBER 27, 1987

2501 M Street, NW • Washington, DC 20037 • Telephone 202/88 -1100 • Telex 89617 (CMA WSH)

The Fluorocarbon Program Panel (Panel) of the Chemical Manufacturers Association (CMA) welcomes this opportunity to provide information on the implications of the Airborne Antarctic Ozone Experiment.

The Panel is an international group representing 19 chlorofluorocarbon (CFC) producing companies with production facilities in 16 countries. Its research program, administered by CMA, was initiated in 1972 to investigate the potential effects of CFCs on the environment. The Panel has spent in excess of $20 million to date on research and has had an annual budget averaging over $1.5 million in recent years. These figures include only the amount provided to government, academic and private research organizations to investigate potential effects of CFCs on the environment. At least an equivalent amount has been spent on research and related activities by individual companies in support of the Panel's program.

The Panel believes that protection of the ozone layer is a global issue requiring international cooperation and coordination of research and monitoring. Based on this belief, our program is coordinated with and complementary to research of government agencies in the United States and in many other countries. The Panel's research program is balanced among field and laboratory measurements, analysis and interpretation.

CFCs, because of their low toxicity, chemical and thermal stability, and lack of flammability are manufactured to serve critical needs in refrigeration, air conditioning, insulation foam, electronic and medical applications and other uses that society considers highly beneficial. They contribute to both worker and consumer safety and help maintain our standard of living. Therefore, they have achieved widespread use throughout the world.

The CFC ozone issue is unique among environmental concerns that have resulted in regulations. Unlike regulations which seek to correct existing damage to the environment or to prevent damage expected in the near future, the Montreal protocol is an unprecedented international agreement which addresses concerns that a long term increase in CFC emissions could lead to a decrease in the total amount of atmospheric ozone over the next century. Indeed, computer model results indicate that sustained growth at significant rates in the emissions of fully halogenated CFCs might cause appreciable ozone depletion during the next century and, as a result, undesirable environmental effects. Recognition of this possibility by industries that produce and use CFCs, environmental groups, and governments has led to a unique international agreement that restricts emissions and assures protection of the ozone layer far into the future.

The Panel has sponsored theoretical calculations to assess the effect of the Montreal protocol on global ozone. A copy of a report summarizing the work is nearing completion and will be provided to the Subcommittees for the Record. The results of the calculations show that:

- Calculated changes in global ozone amounts based on a true global freeze at 1986 levels are smaller than natural ozone variations that have been observed over the past 30 years. The first and least stringent control measure of the protocol effectively freezes CFC emissions at 1986 levels.

- There is no need to move toward greater reductions or shorter time periods than those set forth in the protocol.

The Montreal protocol provides a reassuring measure of environmental protection by imposing emission controls that go beyond the initial freeze. Because uncertainties in the science remain, the protocol also requires periodic review of scientific, environmental, technical, and economic information to assess the adequacy of the CFC emission controls. This review provision ensures continued environmental protection without unduly sacrificing the valuable contributions of CFCs to worker and consumer safety and to our standard of living.

The periodic reviews specified by the Protocol will, of course, critically consider new scientific information such as that from the recent expedition to Antarctica.

There are two fundamental questions regarding the Antarctic ozone "hole" phenomenon. First, what is the basic cause of seasonal ozone decreases over Antarctica? And second, does the phenomenon have global implications?

The expedition to Antarctica has yielded much new information, but from an analysis of the early results it appears the fundamental cause of the phenomenon is still uncertain. Scientists have concluded that both unique meteorology as well as perturbed chemistry are involved. Meteorology contributes directly to some of the decreases. Thus, a "hole" of some proportion would probably be present even if man-made chlorine compounds had never been emitted into the atmosphere.

In addition, the severe meteorology creates a unique chemical environment. Within this unique region, a perturbed chemistry exists -- a chemistry different from what scientists assume for the rest of the stratosphere. The preliminary findings indicate that the perturbed chemistry contributes to a portion of the ozone decreases. At present, we cannot determine the relative contributions of meteorology and chemistry to the seasonal decreases of ozone above Antarctica.

On the question of global implications, our current understanding indicates that perturbed chemistry within this region is not likely to occur elsewhere and contribute to global ozone depletion. Published information and the preliminary findings of the recent airborne experiments clearly show the unique character of the Antarctic during the periods that ozone decreases have been observed. Even in the other most similar region of the world, the Arctic, the meteorology effectively precludes a similar situation. Unique meteorological conditions, found only over Antarctica, are required to establish this perturbed chemical environment.

While the overall mission was very successful, and much informative data was collected, the preliminary findings of the Airborne Antarctic Ozone Experiment have not provided absolute answers to the two questions posed earlier. This underscores the need for: complete analysis of the data by the scientists involved; continuation of complementary laboratory kinetics studies; and review by the science community. These tasks should be completed well before the 1989 science review which will serve as input to the policy review of the Montreal protocol due in 1990.

We agree with the mission scientists that until that time, the findings should be considered preliminary in nature and should not be used as a basis for policy decisions.

CMA

CHEMICAL MANUFACTURERS ASSOCIATION

November 10, 1987

Honorable Max Baucus, Chairman
Subcommittee on Hazardous Wastes and Toxic Substances

Honorable George Mitchell, Chairman
Subcommittee on Environmental Protection
Committee on Environment and Public Works
United States Senate
Washington, DC 20510

Reference: Joint Hearing on Implications of the Fall Expedition to Investigate the Antarctic Ozone Hole on Stratospheric Ozone Depletion, October 27, 1987

Dear Senator Baucus and Senator Mitchell:

Enclosed is a paper entitled "Stratospheric Ozone Projections in Light of the Montreal Protocol" to supplement Dr. McFarland's statement made on behalf of the CMA Fluorocarbon Program Panel at the referenced hearing. This paper contains comprehensive model calculations that show the effectiveness of the Montreal Protocol in protecting stratospheric ozone.

As illustrated in the lower graph in Figure 2 (opposite page 14), on the basis of the best current scientific information the Montreal Protocol is highly effective in keeping stratospheric ozone almost constant over the next century. Comparison of this graph with the lower one in Figure 3 (opposite page 15), which depicts the consequences of continued growth in CFC and Halon emissions at 2.5% per year, shows dramatically the effectiveness of the Protocol measures that were agreed upon in Montreal.

Furthermore, the Protocol is a living document which has built-in processes for assimilating future changes in scientific understanding and making adjustments in control provisions that may be required to ensure continued environmental protection.

We wish to call your attention to another matter. At the referenced hearing another witness expressed concern about the safety of scientists working in areas of the Antarctic where the seasonal decline in stratospheric ozone has occurred. He voiced the opinion that the intensity of ultraviolet radiation at ground level might be several times that occurring on a summer day in Miami, Florida. References to these comments appeared in subsequent press reports on

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October 28 including The New York Times (page A13) and The Washington Post (page A9).

We wish to note that these concerns appear to be unfounded. In addition to our paper, I also enclose a one-page discussion of calculations showing that the UV reaching the ground in Antarctica is always much smaller than that reaching the ground at noon during summer in Miami.

Please let me know if we can supply any other information that could be helpful to the Subcommittees.

Sincerely,

Geraldine V. Cox

Geraldine V. Cox, Ph.D.
Vice President-Technical Director

Mack McFarland

Dr. Mack McFarland, Member
Fluorocarbon Program Panel

Enclosures

ENCLOSURE I

CHEMICAL MANUFACTURERS ASSOCIATION

STRATOSPHERIC OZONE PROJECTIONS IN LIGHT OF THE MONTREAL PROTOCOL

presented by

Dr. Mack McFarland
on behalf of the
Fluorocarbon Program Panel
CHEMICAL MANUFACTURERS ASSOCIATION

to

First North American Conference on
Preparing for Climate Change:
A Cooperative Approach

organized by the
Climate Institute

Washington, D.C.

October 28, 1987

Introduction and Summary

The chlorofluorocarbon-ozone issue is unique among environmental concerns that have resulted in regulations. Unlike regulations which seek to correct existing damage to the environment or to prevent damage that is expected soon, the Montreal protocol is an unprecedented international agreement aimed at averting a problem for the future.

The original concerns were based on computer model results indicating that sustained growth at significant rates in the emissions of fully halogenated CFCs could cause appreciable ozone depletion over the next century and, as a result, undesirable environmental effects. The Montreal protocol addresses this problem by limiting CFC emissions.

In fact, the protocol now provides an extra measure of protection by requiring emissions controls that will limit changes in global ozone amount to levels that are much smaller than natural variability. Additionally, because uncertainties in the science remain, the protocol requires periodic review of scientific, environmental, technical, and economic information to assess the adequacy of the CFC emission controls.

In the effort to reduce risk to the ozone layer, however, we must avoid overregulation. CFCs serve critical needs in many uses that society considers highly beneficial. Products and materials like modern refrigeration, automotive air conditioning, energy-efficient insulation, critical electronic and medical applications would be impossible today without CFCs. Regulation beyond a scientifically justified safety level will cause unnecessary hardships and potential hazards for society. The review provision of the protocol ensures continued environmental protection without unduly sacrificing the valuable contributions of CFCs to worker and consumer safety and our standard of living.

In this paper the Fluorocarbon Program Panel (FPP) of the Chemical Manufacturers Association (CMA) presents model calculated ozone changes in light of the Montreal protocol. Results of these calculations show that:

- o Calculated changes in global ozone amounts based on a true global freeze at 1986 levels are smaller than natural ozone variations that have been observed over the past 30 years. The first and least stringent control measure of the protocol effectively freezes CFC emissions at 1986 levels.

- o Based on the CFC reductions additionally specified in the protocol, global ozone amounts are calculated to be almost constant over the next century.

Atmospheric Models and Uncertainty

Scientists and policy makers need an accurate method to forecast changes in atmospheric ozone. Forecasts over at least 10 to 20 years are required for policy decisions. Laboratory simulation experiments are inadequate for this purpose because the atmosphere is too large and complex. Thus, the only viable alternative is use of computer models designed to simulate the atmospheric processes that control the concentrations of ozone.

As in all attempts to represent complex natural processes, atmospheric modeling involves the use of approximations as model parameters are not always precisely known. Comparisons with atmospheric measurements indicate that model results can provide reasonably reliable predictions for the next few decades. However, inherent model uncertainties should be kept in mind in making longer term forecasts.

Uncertainties in model results come from several simplifying assumptions and from deficiencies in our understanding of the inputs required for calculations. Major sources of uncertainty are:

o Future concentrations of CFCs and all other trace gases that can affect ozone;

o Simplifications required to simulate the three dimensional motions of the atmosphere;

o Inaccuracies in the physical constants characterizing the photochemical reactions important in controlling the ozone balance; and

o Completeness of the model -- whether the model accounts for the major processes responsible for controlling atmospheric ozone.

The Montreal protocol impacts the first source of uncertainty by placing limits on global CFC emissions. This virtually eliminates the high-side uncertainty associated with projections of future concentrations of CFCs.

To evaluate the remaining three sources of uncertainty, scientists test the models by comparing calculated concentrations of atmospheric species with measured values. Overall, these comparisons indicate that models simulate many characteristics of the atmosphere reasonably well. However, there are several important differences between calculated and measured concentrations which limit scientists' confidence in the long range predictive capability of models.

The short term predictive capability is better. A comparison of model calculated and measured concentrations of chlorine monoxide, the key compound in the chlorine catalyzed ozone destruction cycle, tests the reliability of model-calculated effects of chlorine, and hence CFCs (a source of chlorine), on ozone. Chlorine monoxide concentrations determine the rate of ozone destruction by chlorine. Measured concentrations are near, but less than, calculated values throughout most of the stratosphere (see Figure 11-1 on page 606 of WMO Report No. 16). This indicates that models are not significantly underpredicting near-term effects of chlorine on stratospheric ozone. The close agreement indicates that the projections of appreciable ozone depletion associated with large increases in emissions of fully halogenated CFCs should be taken seriously. Thus, precautionary measures to limit growth in CFC emissions are justified. Most importantly, the results of the comparison establish confidence in short-term model forecasts that predict ozone changes associated with constant emission rates of CFCs that are smaller than natural variability.

The recent report of elevated abundances of chlorine monoxide within the 'chemically perturbed' region of the Antarctic vortex does not modify the conclusion drawn above. Preliminary findings reported by scientists participating in the Airborne Antarctic Ozone Experiment indicate that unique meteorology sets up special conditions necessary to maintain the elevated chlorine monoxide concentrations. There is no evidence to suggest that these severe meteorological conditions could ever occur elsewhere. Thus, at this time there is no reason to believe that chlorine monoxide abundances in the chemically perturbed region have any relevance to the rest of the atmosphere. However, should final analysis indicate that further steps are necessary to protect the environment, the review process in the protocol will allow governments to react rapidly.

Scenarios of Future Trace Gas Emissions and Concentrations

With minor exceptions, limits to future global emissions of fully halogenated CFCs and Halons are well defined by the Montreal protocol. CFC and Halon emission scenarios specified in the protocol (including two different assumptions for CFC emissions in developing countries) are used as the basis for the calculated results presented in this paper. Results of calculations assuming constant emission rates and sustained growth in emissions are also presented for comparison. All emission scenarios used are fully specified in Appendix I.

For the purposes of these calculations, the FPP has adopted the following two emission scenarios for controlled substances in developing countries: (1) an initial emission rate of 10 percent of the global total (excluding emissions under

Article 2.6 of the protocol) in 1990 with an annual rate of growth in emissions of 5 percent per year until 1999, when emissions begin to decrease as specified in paragraphs 3 and 4 of Article 2 of the protocol; and (2) identical to (1) except a growth rate of 10 percent. Economics and technology will provide incentives to limit growth in these countries.

Assumptions most commonly used by atmospheric modelers for future concentrations of carbon dioxide, methane and nitrous oxide were used as input for all of the calculations. The assumed future concentrations for these gases are specified in Appendix I.

Description of Model

Model results discussed here were provided by Atmospheric and Environmental Research, Inc (AER). Results were obtained using a one-dimensional model incorporating the 1987 NASA/Jet Propulsion Laboratory recommended chemical kinetics and photochemical data. Results of the model have been published in many peer-reviewed journal articles and scientific assessment reports (e.g., WMO Report No. 16). The AER model was used by Dr. N. D. Sze during his participation in the model intercomparison held in Würzburg, Federal Republic of Germany and sponsored by the United Nations Environment Programme*. For a specified scenario of future concentrations of CFCs, methane, carbon dioxide, and nitrous oxide, the various atmospheric models compared in Würzburg agreed very well in their calculations of globally averaged ozone change. Therefore, the

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* UNEP/WG.167/Inf. 1

AER model results are representative of one-dimensional model results used during protocol negotiations. In fact, in the Würzburg model comparison, a scenario similar to Scenario 1 in this paper was used. The AER model calculated approximately one percent greater ozone depletion in 2050 than that calculated by the Lawrence Livermore National Laboratory model (used by EPA in their risk assessment).

Results

Model calculated ozone changes over the period 1940 to 2060 for the four CFC and Halon emission scenarios described earlier are presented in Appendix II. Important features of the calculated ozone changes are described there.

Emissions of CFCs maintained at 1986 levels lead to calculated changes in global ozone amounts that are smaller than natural changes that have been observed over the past 30 years. Results for this emission scenario are shown in Figure 1 along with results from analyses of the 30 year data record of ground-based ozone measurements. The measurements indicate that global ozone amounts have varied (both increases and decreases have been observed) by about 3 percent over periods of about a decade. These variations are believed to be due to natural causes. Model results based on an assumption of constant emissions of CFCs at 1986 rates indicate that depletion would be smaller than 3 percent. Calculated ozone amounts gradually deplete to a value in 2060 only 1.5 percent below the level calculated for an atmosphere containing almost no CFCs (the 1940 atmosphere).

The two calculations based on the Montreal protocol indicate that ozone amounts would remain almost unchanged over the next century. Calculated ozone amounts (results for both these calculations are displayed in Figure 2) first decrease slightly to a value only 0.7 percent below 1940 levels in about 2005 and then increase to a value 0.1 percent smaller than 1940 amounts by 2060. Also, the results are very insensitive to choice of emissions growth rates in developing countries. The maximum difference between calculated ozone amounts for the assumed emissions growth rates of 5 and 10 percent for developing countries is only 0.05 percent.

In order to see the impact of the Montreal protocol, one can compare the above results with calculations based on CFC and Halon emissions allowed to increase at a rate of 2.5 percent per year (i.e., a six-fold increase in 70 years). Model results for the growth scenarios indicate that ozone amounts could decrease appreciably by the middle of the next century. With this assumption, emission rates of CFCs increase rapidly, and lead to rapidly increasing concentrations of chlorine in the stratosphere. These large increases in chlorine concentrations lead to a calculated ozone depletion of 23 percent by 2060 (see Figure 3). This model result, which has been the focus of most discussions of the ozone issue, is now precluded by the international agreement.

Conclusions

Two major conclusions can be reached from the information presented in this paper.

First, the control measures contained in the protocol ensure an extra measure of environmental protection by requiring emission reductions beyond what current science indicates is required to maintain global ozone amounts within the limits of natural variability. Current scientific information indicates that even the first and least stringent control specified in the protocol -- a true global freeze of emissions at 1986 rates -- would result in ozone changes that are smaller than natural long term variability throughout the next century. The protocol calls for a two step reduction of emissions beyond the freeze, resulting in almost no change in calculated ozone amounts.

Second, within the provisions of the protocol, control measures can, if scientifically justified, be modified rapidly to ensure continued protection of the ozone layer. The protocol contains provisions to periodically-review scientific, environmental, technical, and economic information to assess the adequacy of control measures. The agreement already takes into account the best information available to protect the environment in the long term, but we know that long range model predictions are uncertain. As new and better information becomes available these predictions will change, and parties to the protocol can respond accordingly in a timely fashion.

Appendix I

EMISSION SCENARIOS

Controlled Substances

Estimated global annual emissions for 1986 are 950,000 metric tons for Group I controlled substances (total emissions of CFCs -11, 12, 113, 114, 115), 4,000 metric tons for Halon 1301, and 4,000 metric tons for Halon 1211. The 950,000 metric tons include 150,000 metric tons based on Article 2.6 of the Montreal protocol. The relative mix of emission rates of the controlled substances is held constant over the period 1986 to 2060. Estimated historical emission rates were used for the period 1940 to 1986.

Scenario 1 - True Global Freeze

Total emission rates of controlled substances including Halons are constant over the period 1986 to 2060.

Scenario 2, Case 1 - Emissions Under the Montreal Protocol

Total emission rates of Group I controlled substances grow at a compounded rate of 5 percent per year over the period 1987 through June 1989. On July 1, 1989, total emission rates are reduced to 1986 rates. After July 1, 1989, the total emissions are split into two groups. During the period July 1989 through July 1993, one group with annual emissions of 870,000 metric tons reduces emissions in 1993 and 1998 in compliance with Articles 2.3 and 2.4 of the protocol. The other group, representing countries operating under Article 5 of the protocol with annual emissions of 80,000 metric tons during July 1989 through June 1990 (10 percent of total emissions exclusive of the 150,000 metric tons based on Article 2.6 of the protocol) increase emissions at 5 percent per year until July 1999, as allowed under Article 5.1 and then decrease emissions in compliance with Articles 5.1, 2.3, and 2.4. Halon emissions are constant over the period 1986 to 2060.

Scenario 2, Case 2 - Emissions Under the Montreal Protocol

Same as Scenario 2, Case 1, except countries operating under Article 5 increase emissions at 10 percent per year over the period June 1990 through July 1999.

Scenario 3 - Growth Scenario (Impossible Under Protocol)

Total emission rates of controlled substances including Halons grow at a compounded rate of 2.5 percent per year over the period 1987 to 2060.

Other Gases - All Scenarios

The scenario for other trace gases' increases are approximately 0.55 percent per year for CO_2, 0.25 percent per year for N_2O, and 0.016 parts per million by volume per year for CH_4.

Appendix II

FIGURES

Figure 1 - True Global Freeze

The top graph presents relative annual emissions (emissions as a function of time divided by emissions in 1986) for the total of the Group I controlled substances (CFCs -11, 12, 113, 114, 115) and for the Halons over the period 1940 to 2060. Actual 1986 Halon emission rates are less than one percent of 1986 Group I emission rates.

The bottom graph presents the calculated percentage change in total ozone (calculated change in total ozone times 100 divided by calculated total ozone in 1940) for the emissions given in the top graph. Relative changes in global ozone amounts as determined by Angell* (triangles) and Reinsel and Tiao* (pluses) from analyses of ground-based measurements of total ozone are also presented.

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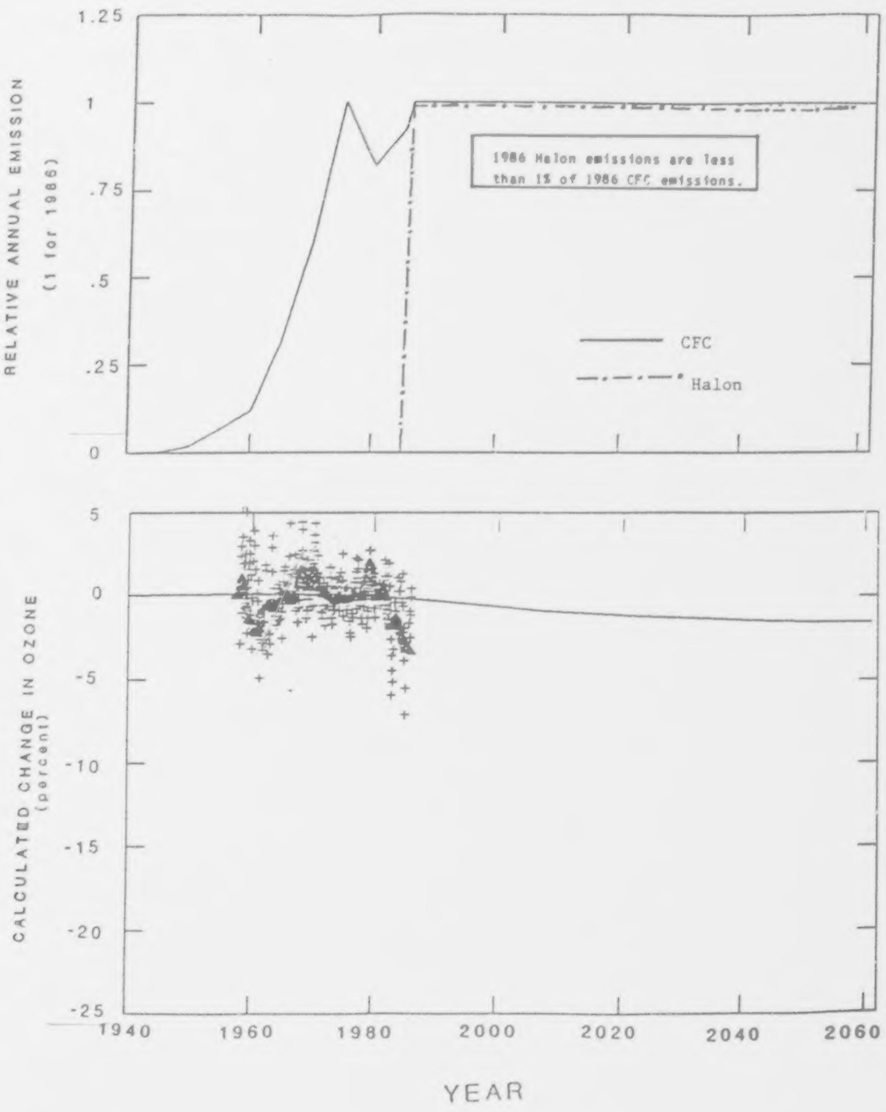
* Personal communication

Figure 1



TRUE GLOBAL FREEZE

Figure 2 - Montreal Protocol Scenarios

The top graph presents relative annual emissions (emissions as a function of time divided by emissions in 1986) for the total of the Group I controlled substances (CFCs -11, 12, 113, 114, 115) and for the Halons over the period 1940 to 2060. Case 1 and Case 2 are described in Appendix I. Actual 1986 Halon emission rates are less than one percent of 1986 Group I emission rates

The bottom graph presents the calculated percentage change in total ozone (calculated change in total ozone times 100 divided by calculated total ozone for 1940) for the emissions given in the top graph.

Figure 2

MONTREAL PROTOCOL SCENARIO

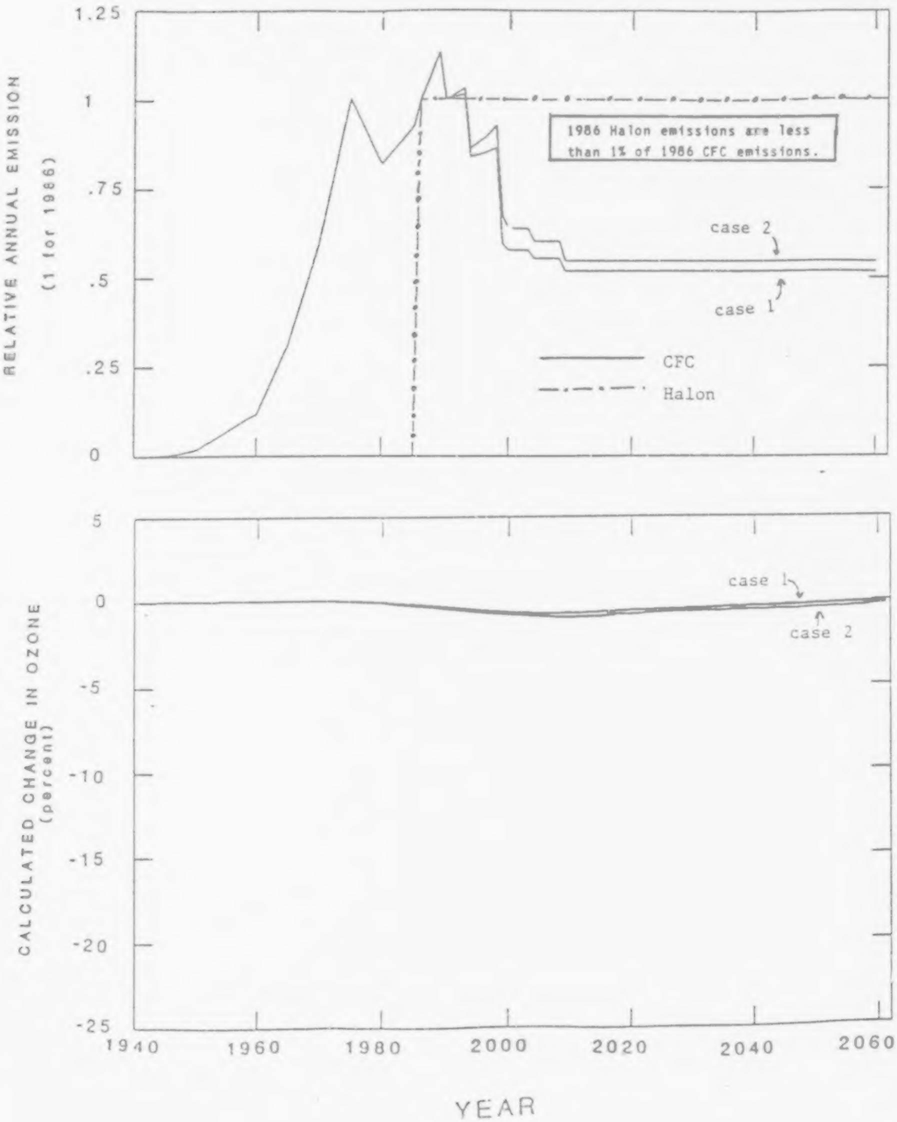


Figure 3 - Growth Scenario (Impossible Under Protocol)

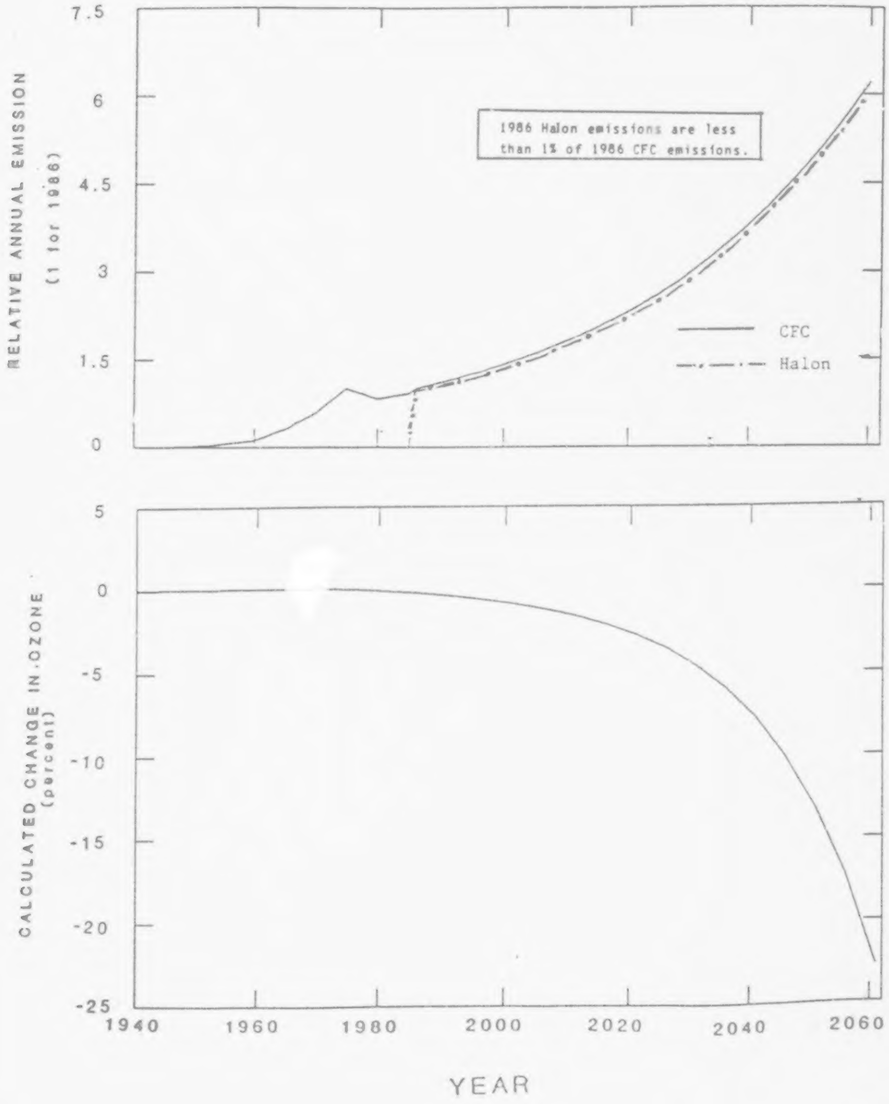
The top graph presents relative annual emissions (emissions as a function of time divided by emissions in 1986) for the total of the Group I controlled substances (CFCs -11, 12, 113, 114, 115) and for the Halons over the period 1940 to 2060. Actual 1986 Halon emission rates are less than one percent of 1986 Group I emission rates.

The bottom graph presents the calculated percentage change in total ozone (calculated change in total ozone times 100 divided by calculated total ozone to 1940) for the emissions presented in the top graph.

Figure 3

GROWTH SCENARIO

(Impossible Under Protocol)



Enclosure 2

Ratio of Ultraviolet Flux:

Antarctica Compared with Miami

At the time of the Antarctic ozone minimum on October 16, 1987, the lowest total ozone amount was slightly over 100 dobson units, or about one-third of the amount present when the ozone "hole" closes again in November. From the October conditions, the calculated noontime biologically active ultraviolet flux at 78 degrees south latitude is approximately half as intense as it is on June 21 in Miami*.

If we make the comparison for mid-summer when the sun is at its highest at both locations, we find that the noontime biologically active UV flux in the Antarctic on December 21 is only one-fifth as intense as it is in Miami on June 21*. This is because by December 21 ozone levels have increased significantly above the Antarctic. Additionally, light from the sun has to traverse a much longer atmospheric path at high latitudes. The biologically active flux used in these comparisons is the energy of all of the ultraviolet light reaching the ground corrected for the absorbing properties of the DNA molecule (the DNA action spectrum).

On the basis of these considerations, the seasonal decline in stratospheric ozone should present no undue hazard to scientists and support personnel working in the Antarctic.

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* Professor John E. Frederick, University of Chicago, private communication.

Testimony presented to the Committee on Environment and Public Works

Subcommittees:

Hazardous Wastes and Toxic Substances

and

Environmental Protection

by

Michael B. McElroy

Abbott Lawrence Rotch Professor of Atmospheric Sciences

Chairman, Department of Earth and Planetary Sciences

Harvard University

Cambridge, Massachusetts

October 27, 1987

Mr. Chairman, Members of the Committee, I appreciate the opportunity to speak to you today on the subject of Antarctic ozone.

Sixteen years have elapsed since Harold Johnston drew attention to the possibility that exhaust gases from supersonic aircraft could cause a reduction in the level of stratospheric ozone. At about the same time James MacDonald, based on a study of epidemiological data on the incidence of skin cancer, concluded that even modest reductions in ozone, as small as a few per cent, could lead to a significant increase in the incidence of skin cancer. In 1973 a number of groups began to study possible effects of chlorine from the space shuttle. It was realized that chlorine was an exceedingly efficient catalyst for removal of ozone. A year later the paper by Mario Molina and Sherwood Rowland appeared in the British journal *Nature* pointing out that decomposition of industrial chlorofluorocarbons could provide a much more important and persistent source than the space shuttle. A few months later, in *Science*, I published, with my colleagues Steven Wofsy and Nien Dak Sze, a projection of the changes in ozone to be expected as a function of time for various possible industrial scenarios. Literally hundreds of papers have appeared since 1975, examining aspects of stratospheric chemistry.. A subject of research considered esoteric in 1971 moved to the front stage of atmospheric science in 1974 and to the front pages of the world's newspapers. It has remained there ever since.

Imaginative techniques were developed in the interim to measure the composition of the stratosphere. The stratosphere was sampled with balloons and aircraft. It was observed from the ground and by satellites. A generation of laboratory chemists grew up motivated to understand the fundamental chemical processes at work in the stratosphere.

All of this was accompanied by advances in our ability to model the atmosphere.

How then can we account for the complete surprise that greeted the report in *Nature* two years ago by Farman, Gardiner and Shanklin, announcing a large decrease in ozone over Antarctica in spring? It appears that the reductions in ozone began about ten years ago. The answer, I believe, is that the chemistry operating in the extreme environment of Antarctica is quite distinct from that at mid latitudes. Our attention since 1971 had been directed mainly to the mid latitude regime. We have been forced now to switch our emphasis to the polar region.

We have made remarkable progress in reacting to the challenge from Antarctica. I would argue that we understand now about 80% of what happens in this extreme environment. Progress has been spectacular since 1985. That we could react so rapidly is tribute to the importance and success of the investment in research made by government and the private sector over the past decade.

The high latitude stratosphere is distinguished by the exceptionally cold temperatures attained in late winter and early spring. We predicted [McElroy et al., 1987; Wofsy et al., 1987] that these temperatures would allow formation of clouds containing crystals of nitric acid and water. A portion of the particles in these clouds, we argued, would grow large enough to fall out of the stratosphere, like snow. Nitric acid and water would be removed by this process, setting the stage for subsequent chemistry of a most unusual character. Hydrogen chloride would be incorporated in the remaining cloud particles. Guided by laboratory experiments of M. Molina, T. Tso, L. Molina, and F. Wang, we expected that reactions of chlorine nitrate on the surface of stratospheric ice particles would release large quantities of Cl_2 and HOCl. In the presence of light, these gases should decompose, providing an abundant source of chlorine radicals. The rapid ensuing loss of ozone would be sufficient to account for the loss observed in the Ozone Hole. The model suggests that the Ozone Hole developed when the burden of stratospheric chlorine exceeded a critical level, when the natural background of unreactive species was overwhelmed by chlorine-containing gases. These processes were incorporated in models and described in papers [McElroy et al., 1987; Wofsy et al., 1987; Salawitch et al., 1987] accepted for publication prior to release of the data from the most recent campaign, the aircraft missions mounted this summer from Chile.

The results from Chile provide a bench mark to assess the reliability of the models. I am confident, based on the data released to date, that this chemical model of the Antarctic phenomenon is on the right track. I draw this conclusion in support of the policy recommendations offered below. There is little doubt in my mind that industrial sources of chlorine and bromine contribute in a major way to the loss of ozone observed in recent years in spring over Antarctica. The need for a policy response is urgent and immediate.

Let me summarize the important new pieces of information as presented at the press conference a few weeks ago. Inside the chemically perturbed region:

(1) the abundance of ClO was exceptionally high, more than 100 times larger than outside. Concentrations of ClO were observed to correlate inversely with ozone - when ClO was high, ozone was low and vice versa;

(2) the abundance of nitrogen oxides in the gas phase was low;

(3) there was evidence for nitrate in the particulate phase;

(4) the abundance of HCl was very low;

(5) the stratosphere was exceptionally dry.

In addition, the press conference reported the first atmospheric detection of the bromine oxide radical and confirmed the earlier measurement of OClO. None of these facts came as a surprise. In light of the evidence from 1987, there can be little doubt that chemical processes play a dominant role in the phenomenon of Antarctic ozone.

When I testified some years ago on the subject of stratospheric ozone, I took a rather cautious approach. I believed that the penalty involved in waiting a few years to test our understanding of the stratosphere against observation, to allow our models to evolve as new data were obtained and assimilated, was not severe. The risk implicit in a delay of a few years justified, I thought, the benefit of a more orderly and informed assessment. Changes in stratospheric ozone were expected to set in gradually. I considered it worth the wait to learn more, to be able to provide more confident advice to government. My confidence in the validity of this approach was shaken by the initial discovery of the Hole over Antarctica. There remained, however, the possibility that it was a natural phenomenon. The results from the National Ozone Expedition last year lent further doubt to the credibility of the cautious approach. The results from this year indicate that it is time to take a stand. There is no longer reason to doubt that industrial gases containing chlorine are responsible for a dramatic large scale change in the stratosphere. It is difficult to remain detached when ozone is essentially eliminated from almost 10% of a hemisphere for a period of almost two months. There is no reason to expect that the loss of ozone that began in 1978 will soon disappear.

I believe that we passed an important threshold in 1978. The Antarctic Hole is here to stay. It may fluctuate from year to year, depending on the prevailing stratospheric meteorology. When the stratosphere is cold it will be severe. When the stratosphere is relatively warm the Hole will be present though less dramatic. It will persist for a hundred years even if we effect a complete immediate ban on release of chlorofluorocarbons. The long lifetime of chlorofluorocarbons guarantees that the Hole will remain a lasting legacy to posterity.

The initiative taken by the United Nations in Montreal deserves our acclaim. It represents an important and balanced approach to the threat posed to ozone at mid latitudes. The cooperation and support of industry in advance of the Montreal Meeting was particularly laudable. The delegates in Montreal were instructed not to consider the Antarctic phenomenon in their deliberations. Our understanding of the phenomenon was considered too rudimentary to have an immediate impact on policy. I did not disagree with that decision. But the situation has now changed. The chemistry responsible for the enormous drop in ozone over Antarctica is distinct. It is quite different from the chemistry that occupied our attention since 1974. It is not a substitute but an addition to the earlier concern. The associated impact in Antarctica sets in, not slowly, but precipitously. It requires an appropriately radical response.

Many organizations and individuals have contributed to the remarkable advances that have taken place in our understanding of stratospheric ozone in recent years. A particular debt of gratitude is due the scientists and pilots who labored hard in Chile to obtain the remarkable results reported at the press conference a few weeks ago. We are indebted likewise to the teams of scientists and support personnel who labored on the ground in Antarctica this summer and last. Without their heroic effort we would remain in the dark. On a personal level I would like to acknowledge the inspiration and dedication of my immediate colleagues over the past year, Ross Salawitch, Steven Wofsy and Mario Molina. Stratospheric research is truly a team effort. There is little the individual can accomplish alone. Progress has involved an unprecedented collaboration of government and industry. The work has been truly international in scope, consistent with the challenge.

There is more to be done. We need to assess the implications of the chemistry observed in Antarctica for other regions of the Earth. Can we expect the Antarctic phenomenon to show up in the Arctic? What implications does it carry for ozone at mid latitudes? We may have opinions individually on these issues, but opinion is no substitute for hard scientific fact. In the interim we must repond to the facts in hand. There is a need for immediate additional cuts in release of industrial chlorinated and brominated hydrocarbons. Montreal showed the way. We must continue the historic precedent set by the delegates at that meeting in September. The stakes are high: we must act to maintain the integrity of the global environment for generations not yet born.

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Implications for Bromine.

(To be published in *Planetary Space Science*, February 1988.)

Wofsy, S.C., M.J. Molina, R.J. Salawitch, L.E. Fox, and M.B. McElroy.

Interactions between HCl, NO_x, and H_2O Ice in the

Antarctic Stratosphere: Implications for Ozone.

(Submitted to *Journal of Geophysical Research*, August 1987.)

TESTIMONY BY PROF. F. SHERWOOD ROWLAND, Department of Chemistry,
University of California Irvine, to the Senate Committee on
Environment and Public Works, Washington, D. C., October 27, 1987

The massive losses of ozone during the Antarctic spring over the past decade have forced a careful re-examination of our understanding of the chemistry of the stratospheric ozone layer. Our information base for such reconsideration has been enormously increased by the intensive experimental studies conducted during the austral springs of 1986 and 1987, on the ground at the U.S. bases in McMurdo and the South Pole, and by the 25 aircraft flights flown from Punta Arenas, Chile. Extensive investigations have also been carried out by expeditions from other countries, including among others, the Japanese at their Syowa station on the Antarctic continent, and the British at their polar stations at Halley Bay and on the Palmer peninsula. The results from these expeditions have clearly demonstrated that the major contributing factor to the Antarctic ozone hole has been the very rapid increase in the total amount of reactive chlorine in the stratosphere, most of it attributable to the surging atmospheric concentrations of the chlorofluorocarbon compounds CCl_2F_2 (CFC-12), CCl_3F (CFC-11) and CCl_2FCClF_2 (CFC-113). This direct experimental confirmation of the importance of man-made chlorine compounds to the loss of 50% or more of the Antarctic ozone during the month of September makes it imperative that we consider the Antarctic phenomuna in detail. We must determine as well as we can not only the immediate consequences in Antarctica, but we must also assess the significance of the Antarctic ozone hole for the future of the south polar region, and for the entire global atmosphere.

It is my belief that the implications are sufficiently serious that the United States and the other countries of the world must move well beyond the control requirements specified in the United Nations protocol signed i Montreal only last month. We must proceed as rapidly as possible toward 95% elimination of the further release to the atmosphere of the perhalo chlorofluorocarbons which are the greatest threat to stratospheric ozone.

First, some comments about the chemistry and physics of the Antarctic stratosphere. I am submitting as an Appendix to my testimony the text of my discussion paper written in early September for the Dahlem Conference on "Our Changing Atmosphere", a conference which convenes in West Berlin next week. This paper describes the chemistry of the Antarctic stratosphere on the basis of the 1986 Antarctic expedition, and upon the many related experimental and theoretical studies carried out during the past two years. The first results of the Punta Arenas aircraft expedition announced on September 30 have substantially strengthened and augmented the details of this description with many important new observations. I am also submitting as an Appendix to my testimony the text of another article, "Can We Close the Ozone Hole?", as published by the journal Technology Review in August 1987.

The Chemistry of the Springtime Antarctic Stratosphere

In brief, the air which is over Antarctica at the beginning of the southern winter remains trapped in the south polar vortex for months and months, becoming colder and colder. In this frigid darkness, polar stratospheric clouds (PSCs) are formed which certainly contain water and nitric acid, and may also contain some sulfuric acid. The particles of these clouds furnish the structural surfaces on which chemical reactions can occur which materially shift the molecular balance of the stratosphere away from that commonly observed in the temperate and tropical zones with their daily alternation of sunlight and darkness:

(a) The usually abundant NO_x nitrogen compounds are converted in the darkness first to the gaseous molecule N_2O_5, and then by reaction with water to nitric acid on the particle surfaces. Once converted to nitric acid, the nitrogen molecules remain attached to the particles, and do not return to the gaseous form until the PSCs evaporate in the spring.

(b) Chlorine which is normally present in the form of the chemical reservoirs hydrogen chloride (HCl) and chlorine nitrate ($ClONO_2$) is transferred by other chemical reactions on the PSC surfaces into the unstable reservoirs of molecular chlorine (Cl_2) and HOCl. These unstable chlorine reservoir molecules escape from the particles back into the free gaseous state, while the nitrogen from chlorine nitrate remains attached to the particles as nitric acid.

(c) Furthermore, air in the Antarctic stratosphere has normally descended from still higher altitudes and latitudes nearer the equator in which it has been thoroughly exposed to solar ultraviolet radiation, and large fractions of the stable molecules originally present in it have been broken down into smaller fragments. Methane (CH_4) has been taken apart, releasing hydrogen which is then oxidized, leading to an increase in the concentration of H_2O available for cloud formation. Nitrous oxide (N_2O) has largely been destroyed in these air parcels. And a large fraction of the organochlorine compounds, e.g. CCl_4, CCl_3F, CCl_2F_2, etc., have also been decomposed releasing chlorine into more chemically reactive forms.

When Antarctic air with this drastically altered chemical composition is struck by the first sunlight of the Antarctic spring, atomic chlorine is immediately released from the unstable chlorine reservoirs Cl_2 and HOCl ; initiates a long chain reaction involving the radicals Cl and ClO which efficiently removes ozone from the stratosphere. This depletion of ozone continues without the major interruptions characteristic of the temperate and tropical chlorine chain reactions because the usual steps which temporarily divert such chain reactions are absent in the Antarctic spring.

Normally, the free radical chlorine oxide (ClO) can combine with nitrogen dioxide (NO_2) to form the relatively stable reservoir molecule chlorine nitrate--but, with NO_x nitrogen trapped in the PSC particles as nitric acid, little or no NO_2 is available to react with the gaseous ClO.

Normally, the other important reactant in the chlorine chain, atomic Cl, can react with methane to form the stable reservoir molecule hydrogen chloride--but, with little methane left in the stratosphere, and with the attack of Cl on CH_4 greatly slowed by the very low temperatures, this diversion process is not very successful either.

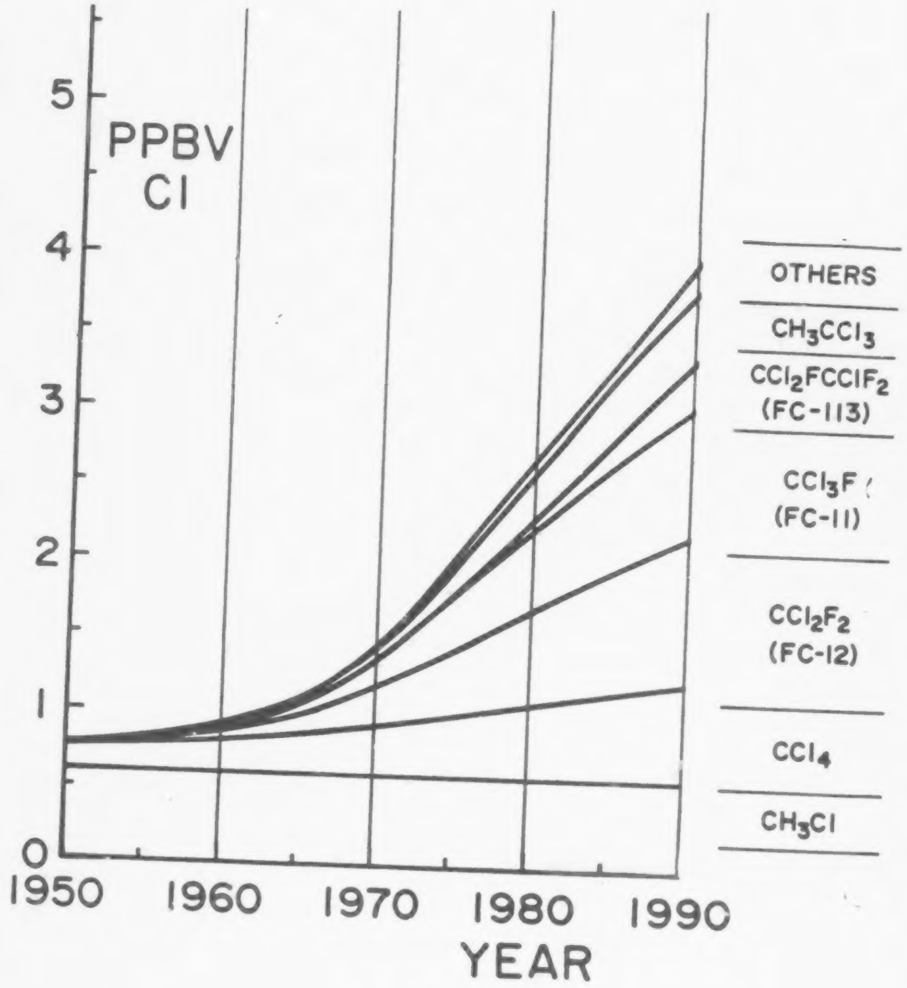
The chlorine chain then proceeds in the Antarctic stratosphere with relatively few interruptions all through the month of September, and on into October. Eventually, the increasing sunlight of late spring evaporates the PSCs, and then breaks down the Antarctic polar vortex with stratospheric air from temperate latitudes.

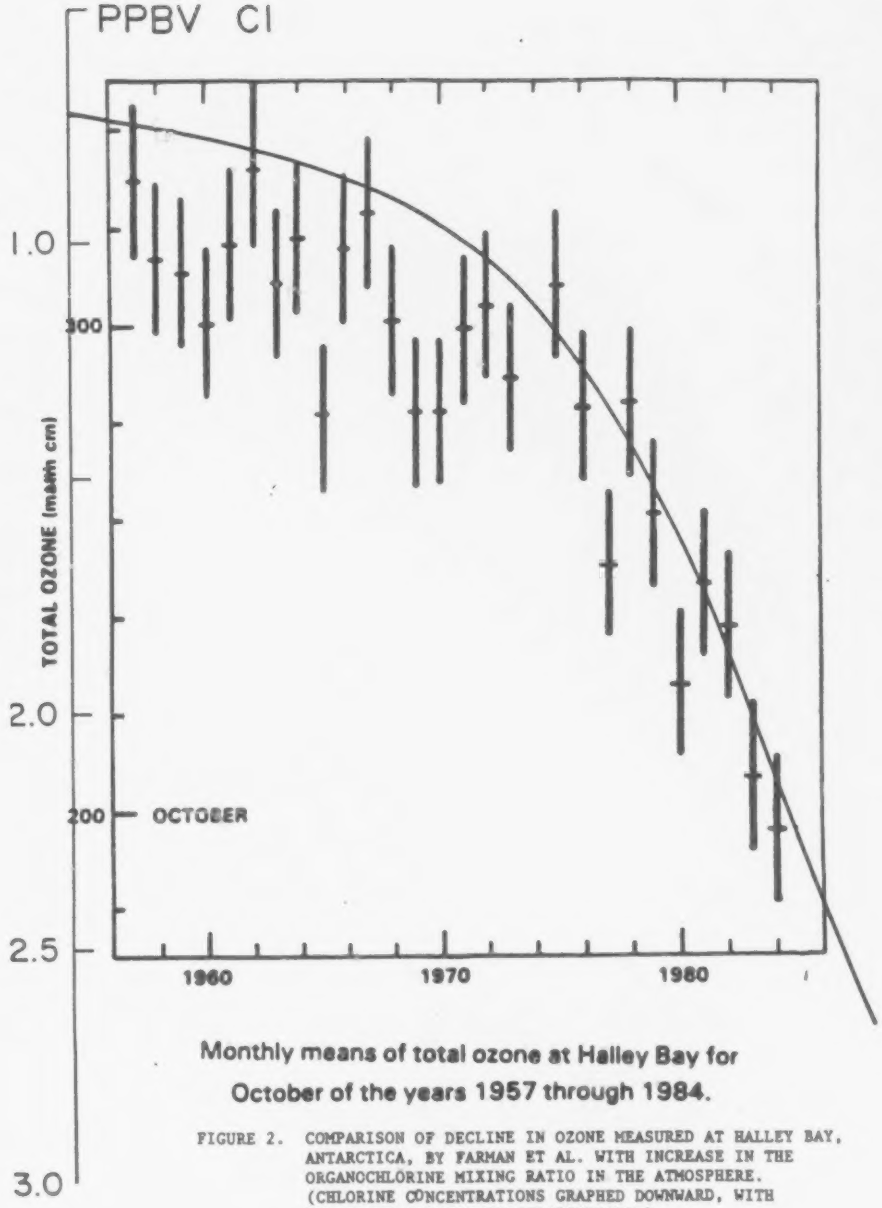
Increasing Atmospheric Concentrations of Chlorofluorocarbons and Methane

The trapping of nitric acid on PSC surfaces presumably has occurred fo many decades or centuries with little consequence for stratospheric ozone because the chlorine concentrations were quite low until the last two decades. However, the very rapid increase in organochlorine mixing ratios since 1960, as shown in Figure 1, has provided the source for the chlorine atoms which so effectively deplete Antarctic ozone during September/October in the 1980s. The total organochlorine mixing ratio of the atmosphere 30 years ago was less than 1 part per billion by volume (ppbv), and is now about 3.7 ppbv in the northern hemisphere troposphere. These concentrations will inevitably appear in the stratosphere globally, after delay periods up to a decade for the slow upward transmission of trace species in the atmosphere. The reports from the Punta Arenas aircraft mission have indicated the presence of the free radical ClO at the level of 1 ppbv--more chlorine in the active ozone-removing chain now than there was total atmospheric chlorine in all chemical forms 30 years ago. A striking reverse parallel exists between the loss of ozone measured over Halley Bay by the British and the increase of chlorine in the atmosphere, as shown in Figure 2 in which the organochlorine increase is graphed downward.

The steady increase in atmospheric methane (Figure 3) is another example of the changes occurring in the atmosphere in recent decades, and has a potential positive feedback into the Antarctic ozone problem. Two important routes exist for getting water vapor into the stratosphere. The first is simply being carried upward as H_2O in rising air; the second involves carrying hydrogen atoms upward in the chemical form of CH_4, and then releasing them as the CH_4 molecule is oxidized. In the 1980s atmosphere these two processes deliver approximately equal amounts of hydrogen to the stratosphere. However, with atmospheric methane concentrations increasing at a rate of about 1% per year, the average amount of water vapor in the stratosphere is presumably steadily increasing with time.

FIGURE 1. GROWTH IN TROPOSPHERIC MIXING RATIOS OF ORGANOCHLORINE COMPOUNDS





Monthly means of total ozone at Halley Bay for October of the years 1957 through 1984.

FIGURE 2. COMPARISON OF DECLINE IN OZONE MEASURED AT HALLEY BAY, ANTARCTICA, BY FARMAN ET AL. WITH INCREASE IN THE ORGANOCHLORINE MIXING RATIO IN THE ATMOSPHERE. (CHLORINE CONCENTRATIONS GRAPHED DOWNWARD, WITH DELAY FOR ARRIVAL IN STRATOSPHERE.)

Measurements of the methane mixing ratios in air trapped in the ice sheets of Greenland and Antarctica 200 years ago have shown its value then was only 0.7 ppmv, less than half of the present value of 1.68 ppmv. Althoug' no confirming measurements exist back over the centuries, it is quite likely that considerably more H_2O is in the stratosphere now than there was 100 or 200 years ago, and the amount is continuing to increase. Clearly, the more H_2O in the stratosphere, the more H_2O available for the formation of PSCs, and the greater the possibility for providing surfaces on which the chemical reactions of N_2O_5 and chlorine nitrate can occur. This feedback process is one in which the increasing amounts of atmospheric methane can potentially act to make the existing amounts of atmospheric chlorine even more effective in depleting ozone; if chlorine concentrations continue to increase, then the ozone removal could be accelerated even more.

Global Significance of Antarctic Ozone Losses

A question of major importance is whether the springtime loss of Antarctic ozone has any carry-over to other latitudes. When the Antarctic polar vortex breaks up in November, stratospheric air from other latitudes comes southward over the continent, displacing to the north the air that was trapped there all winter long. Obviously, this stratospheric air from Antarctica carries much less ozone northward into the south temperate zone in the 1980s than did the corresponding northward-moving air parcels in the 1960s and 1970s, and this must show up, at least initially, as a quantitative deficit at these other latitudes. Indeed, the Nimbus-7 satellite measurements of ozone have been showing progressively less ozone at other southern hemispheric latitudes during successive Antarctic summers in the 1980s. Five percent of the entire atmosphere covers the latitudes between

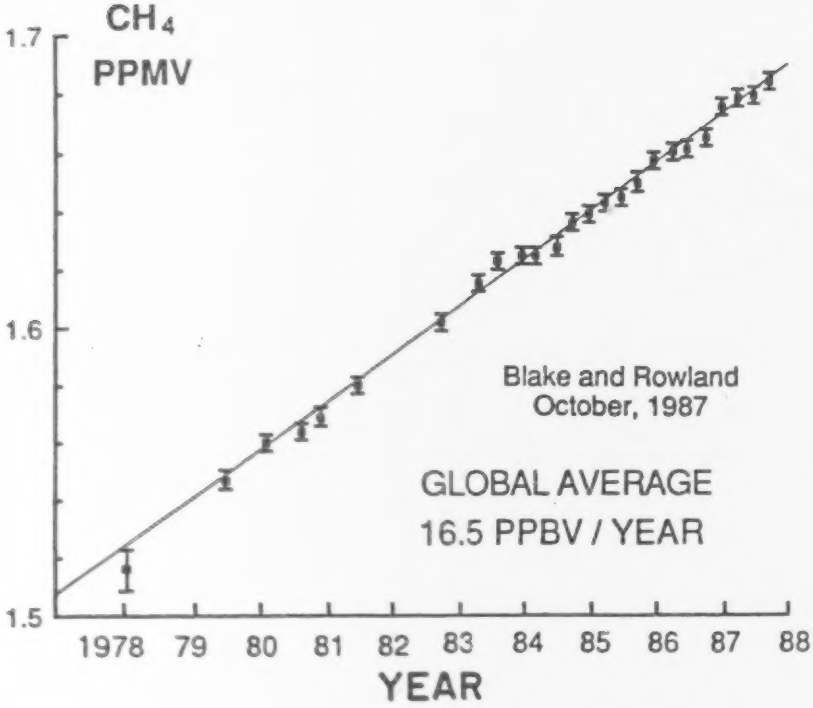


FIGURE 3. GROWTH IN TROPOSPHERIC MIXING RATIO OF METHANE

64°S and the south pole, and ozone losses originally confined to that region can eventually be distributed world-wide. The difficulty in making such loss accounting quantitative is that ozone is in a constant dynamic equilibrium. Ozone is created by solar ultraviolet radiation interacting with the molecular oxygen of the atmosphere, while at the same time other molecules of ozone are being destroyed reactive molecular fragments also released by solar ultraviolet radiation. The amount of ozone present is always determined by the balance between these production and loss processes. In principle, however, some ozone loss must be recorded at latitudes away from the Antarctic ozone hole as the ozone-depleted air is exported northward in November.

Heterogeneous Chemical Reactions in the Stratosphere

A more important question concerns whether the chemical mechanisms which remove ozone in the Antarctic springtime have any counterparts at other latitudes. My answer to this question is, qualitatively, "Yes." However, I cannot provide any blueprint for predictions of the quantitative importance of such chemical effects in the temperate and tropical stratosphere. The difficulty lies in the nature of heterogeneous chemical reactions--those which take place on surfaces such as those of stratospheric clouds. These reactions are notoriously dependent upon the precise characteristics of the individual surfaces, with reaction rates varying widely for seemingly similar surfaces, but which are individually different for example in their roughness or other structural peculiarities. We know that particles are always present in the lower stratosphere for all latitudes, with larger numbers after recent volcanic activity, but still existing even after periods of volcanic inactivity. We know relatively little about the sizes and shapes of these particles, even about their chemical composition. The lower stratospheric particles in temperate latitudes have appreciable amounts of sulfuric acid in them; nitric acid is a frequent ingredient, together with variable amounts of water.

We know that the nitrogen molecule, N_2O_5, reacts very rapidly with water on all of the inert surfaces yet tried in laboratory experiments. We know, too, that the chlorine reservoir molecule chlorine nitrate reacts extremely rapidly with either water or with hydrogen chloride on all of the surfaces tested so far. We know that the observations of chemical change accompanying the Antarctic springtime ozone depletion are consistent with the same reactions taking place on the PSC surfaces. With this knowledge, it would be foolhardy indeed to assume that the same reactions cannot occur on the particles found in the temperate zone stratosphere. But we can't make good quantitative predictions of how fast these reactions will occur in the temperate zone--and we won't be able to even if we have a perfect understanding of the reactions as they occur in the Antarctic stratosphere--because the temperate zone particle surfaces are different from the PSC particle surfaces. The rates of chemical reaction on these two kinds of surfaces are probably also different, but in ways not yet subject to direct experiment. My opinion is that the quantitative importance of surface reactions in the temperate and tropical zone stratosphere will have to be settled through actual *in situ* field measurements carried out with high altitude aircraft and balloons.

Measured Changes in Total Ozone Over the North Temperate Zone

Measurements of the total ozone concentration in the atmosphere can be made from the ground by direct observation of the amounts of ultraviolet radiation arriving from the sun at two or more wavelengths. This technique was established on a quantitative basis more than 60 years ago, and regular measurements were begun at several locations in Europe in the 1920s and 1930s. The longest continuous record of ozone concentrations above a fixed ground station is the series from Arosa, Switzerland, with monthly averages available since August 1931. The analysis of these data by Neil Harris working with me at the University of California Irvine has shown a marked decline in the average ozone concentrations, especially in the winter months, as shown in Figure 4. Most of this change has occurred during the past decade, and indicates a maximum loss of almost 9% in the average amount of ozone over Switzerland during each March. Harris and I have made similar comparisons with the data from the U.S. ozone-measurement stations at Bismarck, North Dakota, and Caribou, Maine, and have again found a significant loss of ozone in the winter months, as shown in Figure 5. The pattern of losses for the different months is rather similar for all three of these ground-based stations, and for several other stations, although not for all. The Arosa/Bismarck/Caribou pattern implies the existence of a seasonally-dependent loss of ozone in these north temperate zone locations. Such statistical analyses provide no information about the actual causes of such wintertime losses of ozone, but some parallel may well exist with the polar Antarctic ozone losses. Because the Arctic polar vortex is not as tight as in the Antarctic, north polar air masses tend not to remain continuously in the darkness for months, but rather to exchange positions with one another rather frequently.

Our examination in the past two years of the extensive ground-based ozone data sets extending back in time for three to six decades leads me to

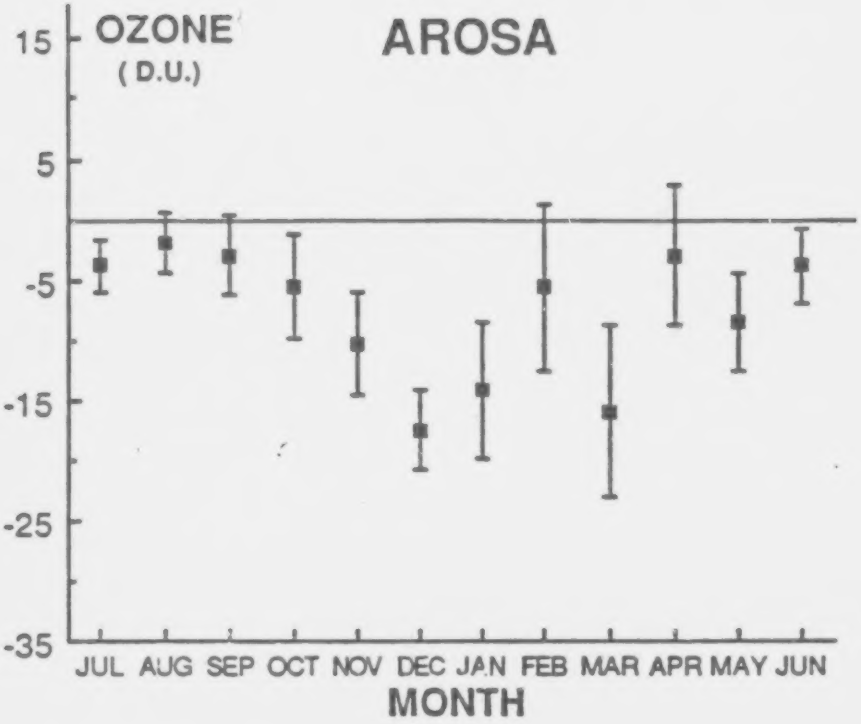


FIGURE 4. AVERAGE MONTHLY OZONE MEASUREMENTS AT AROSA, SWITZERLAND. THE AVERAGE VALUE FOR THE PERIOD 1931-1969 HAS BEEN SUBTRACTED FROM THE AVERAGE VALUE FOR THE PERIOD 1970-1986. MONTHLY VALUES BELOW THE LINE INDICATE LESS OZONE PRESENT DURING 1970-1986 THAN DURING THE EARLIER 40-YEAR PERIOD.

DATA TAKEN BY THE E.T.H., ZURICH (H.U.Dutsch)

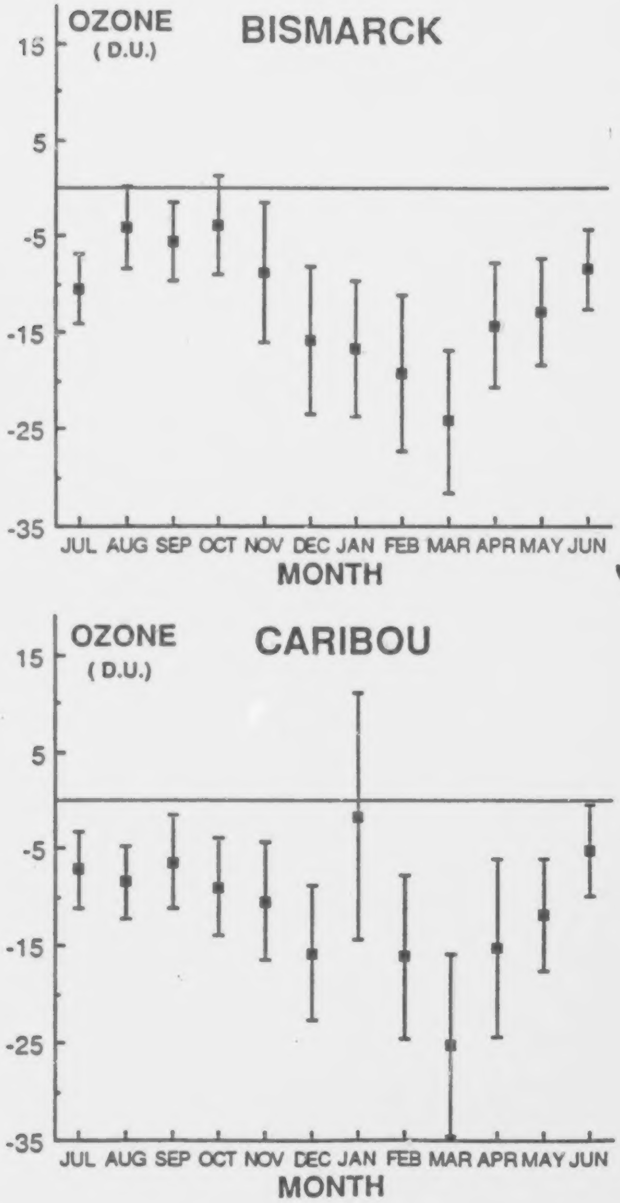


FIGURE 5.

AVERAGE MONTHLY OZONE VALUES AT U.S. STATIONS IN BISMARCK, N. DAKOTA, AND CARIBOU, MAINE.

AVERAGE VALUES FOR THE PERIOD 1963-1974 HAVE BEEN SUBTRACTED FROM THE AVERAGE VALUES FOR THE PERIOD 1975-1986. MONTHLY VALUES BELOW THE LINE INDICATE LESS OZONE PRESENT DURING 1975-1986 THAN DURING 1963-1974.

make some parenthetical remarks about such data. Let me add immediately that my research group and I have had no connection with any of the actual measurements from these ground-based stations, but are simply working with the data reported by the individual scientists in the various countries supporting such grouond-based stations.

The atmospheric science community is indeed fortunate that a small number of dedicated individuals, both in the United States and in other countries, has persevered in making ozone measurements over a very long period of time with sufficient quality that significant statements about changing ozone concentrations can now be made. At times in the past, the financial support for such measurements in the United States and in the other countries has been very, very thin. Even at present, the amounts of money going into these ground-based measurements are very small, and some desirable experimental extensions of this work cannot be carried out because of a shortage of scientific talent funded for such work.

The ground-based stations are now playing a dual role, and will undoubtedly continue to do so in the coming decades. First, these stations measure ozone daily for a limited number of fixed locations around the globe, with instruments whose characteristics are well-known, and which are subject to periodic recalibration and intercomparison. Not all of the stations have been uniformly well run over the past 30 years, but a substantial number have been, and an excellent data base of good measurements does exist.

The second role for these ground-based stations is as the "ground truth" tests and calibration of the satellite-borne instruments. The satellite instruments provide detailed daily global coverage--almost

200,000 individual ozone measurements per day with the TOMS instrument on Nimbus 7--in a manner not possible with ground stations at 40 or 100 fixed locations. However, some critical parts of the instruments installed on satellites orbiting outside the atmosphere are necessarily exposed daily to the full force of the sun's ultraviolet radiation, and exhibit serious degradation problems over the course of a decade of measurements. While expert attempts have been made to evaluate the effects of such instrument degradation on the satellite ozone measurements, it is still critically important to be able to validate these degradation corrections with the "ground truth" of comparisons between the ozone values recorded by the satellite instrument as it passes overhead and those measured at the same time by the individual ground stations. I believe that is critically important that additional support at the level of $1,000,000 per year be provided for the next decade for the measurements made by these U.S. grou stations.

The Montreal Protocol on Substances that Deplete the Ozone Layer

The United Nations Protocol for control of chlorofluorocarbons (CFCs), signed on Sept. 16, 1987, in Montreal, represents an important forward step because it demonstrates international agreement that the atmospheric release of the chlorofluorocarbons is a major threat to the earth's stratospheric ozone layer. The acceptance of the Protocol with an eventual decrease by 50% in the yearly atmospheric emissions of CFCs has sent a signal to the CFC manufacturers, to the companies in the CFC-user category, and to the population in general that many of the existing uses of CFCs will not survive indefinitely. With this knowledge, the numbers of people thinking about and working on the replacement of the existing uses has been greatly increased, and the likelihood of success in finding such substitutions has been proportionately enlarged.

For most of the past decade, the search for CFC alternatives has been largely confined to the CFC manufacturers. Quite naturally, their concerns have almost entirely been directed toward CFC-like compounds which are lesser threats to stratospheric ozone--either hydrogen-containing CFCs in the mode of molecules such as $CHClF_2$ (CFC-22, the compound used as the coolant in home air-conditioners) or CH_3CCl_3 (methylchloroform, a widely used degreasing agent); or chlorine-free fluorocarbon compounds such as CH_2FCF_3 (FC-134A). Actually, even these CFC-clone investigations were essentially non-existent from 1980 until mid-1986, when the search for substitutes has begun in earnest. The Montreal agreement on the Protocol has brought many more players into the game of finding appropriate alternatives. The fast food company, McDonalds, which recently announced its intention of finding a replacement within 18 months for its insulated plastic packaging, now made with CFC-11, is certainly not going to wait the 7 to 10 years the chlorofluorocarbon companies have given as the time scale for their development of substitute molecules. The September signing of the Protocol has undoubtedly caused many more companies to join the group searching for replacements within the next year or two, and most of these are probably seeking an alternative which has no relationship to stratospheric ozone depletion. Earlier examples in the United States were the development in 1975-1977 of the pump-valve and roll-on dispensers, and the hydrocarbon propellant systems, as replacements for the CFC propellants used so widely in aerosol cans until the U.S. ban on their use in 1978.

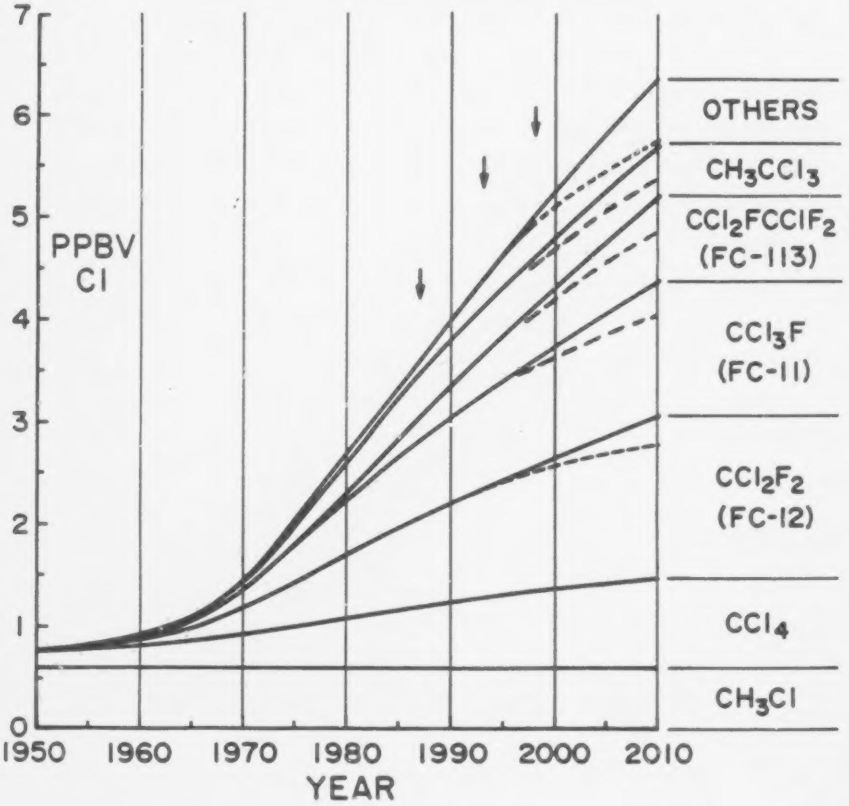
None of these replacements involved CFC-like compounds, and many current uses will likely disappear into non-CFC parts of the economy.

That's the good news about the protocol.

The bad news is that the proposed controls will have relatively little effect on the amounts of chlorine in the atmosphere before the year 2000. The organochlorine concentration in the atmosphere is now about 3.7 ppbv, and is increasing at more than 0.1 ppbv per year, as shown earlier in Figure 1. The controls proposed in the Montreal Protocol include a freeze in emissions in 1990 at 1986 levels; a reduction in yearly emissions by 20% in 1994; and a further reduction in emissions by another 30% in 1999. However, the control of atmospheric concentrations of chlorine is very much more difficult than the control of atmospheric emissions, which is difficult enough politically, and the cumulative atmospheric concentration--not the fresh yearly emissions--control stratospheric ozone depletion.

The expected growth in total chlorine with thef Montreal Protocol in effect will still result in an increase to more than 5.0 ppbv by the year 2000, and a continuing upward trend well into the 21st century, as illustrated by the dashed lines in Figure 6. The very long lifetimes of molecules such as CCl_2F_2 and CCl_3F, measured to be about 110 and 75 years, respectively, insure that the only way to hold atmospheric chlorine concentrations near present levels is a complete cessation of emissions. In effect, the Protocol permits substantial reduction in atmospheric emissions of chlorofluorocarbons to be delayed for a dozen years until 1999 A.D. If atmospheric emissions of CFCs actually reach the full magnitudes permitted by the Montreal Protocol, then a steady, rapid increase in atmospheric chlorine will continue for the rest of this century.

FIGURE 6. EXPECTED GROWTH IN ORGANOCHLORINE CONCENTRATIONS IN THE ATMOSPHERE. SOLID LINE INDICATES PAST GROWTH, AND EXPECTED FUTURE GROWTH IF THE YEARLY EMISSIONS OF THE CHLOROFLUOROCARBONS REMAIN CONSTANT AT THE 1986 LEVELS. DASHED LINES INDICATE THE EXPECTED FUTURE GROWTH IF THE EMISSIONS ARE REDUCED BY 20% in 1994 AND BY 50% IN 1999. ARROWS INDICATE THE PRESENT TIME, AND THE TIME OF EACH OF THE TWO CUT-BACKS OUTLINED IN THE MONTREAL PROTOCOL OF SEPTEMBER 1987.



The timing problem is even more urgent than appears from consideration of the organochlorine concentrations in Figure 6 for two primary reasons. First, about 10% of the chlorofluorocarbons already manufactured have not yet been released to the atmosphere, remaining enclosed for example in polyurethane foam insulation, or in refrigeration coils. Second, and more important, an appreciable delay exists between the release of CFCs to the atmosphere and the full ozone depletion from these compounds in the stratosphere--a delay of about a decade or more. Even if manufacture of CFCs were to cease completely tomorrow, the maximum stratospheric ozone depletion from the CFCs already released would not take place for about 10 to 15 years.

We need to act now, and impose severe restrictions on CFC emissions immediately if we want to bring the chlorine concentrations in the atmosphere under control by early in the next century. The Montreal Protocol permits the postponement of any serious decrease in yearly CFC emissions until the end of the century, and will therefore allow postponement of the control of atmospheric chlorine concentrations for 25 years or more. With such enormous losses of ozone already being observed in the Antarctic spring, and some losses now seen over the north temperate zone, I don't think the global community can afford to wait for another dozen years before applying stringent controls on CFC emissions.

Controls of Compounds not Covered by the Montreal Protocol

The prime compounds of concern relative to stratospheric ozone depletion have been since 1974 the saturated perhalo chlorofluorocarbons, compounds such as CCl_3F (CFC-11), CCl_2F_2 (CFC-12), and CCl_2FCClF_2 (CFC-113). Two classes of molecules not included in this category are the olefinic compounds (e.g. $CHCl=CCl_2$; $CCl_2=CCl_2$) and the hydrochlorofluorocarbons such as $CHClF_2$ (CFC-22)--in both cases, these compounds can be destroyed in the lower atmosphere, the great majority of the molecules never reach the stratosphere, and there is much less threat to the ozone in the stratosphere. The United Nations Vienna Convention signed in 1985 continued to describe the ozone depletion problem in terms of this general class of perhalo CFCs. However, in the Protocol agreed upon in September in Montreal, the compounds directly scheduled for future reductions in emissions are listed specifically in Annex A, Group I, and now contains five molecules: CFC-11, CFC-12, CFC-113, CFC-114 and CFC-115. The first three are the most widely used chlorofluorocarbons, and the latter two are currently used at moderate levels. However, at least two additional CFCs are advertised as commercially available, CFC-112 ($C_2Cl_4F_2$) and CFC-13 ($CClF_3$), each of which possesses the same essential inertness in the lower atmosphere that makes them a stratospheric ozone threat. While these compounds are not in major use, they are commercially available and I have already heard reports of U.S. companies aggressively marketing CFC-112 as a substitute for the CFCs listed in Annex A. I have also been told that CFC-112 has been proposed as a substitute by some Japanese companies.

I believe it is important that the Senate consider legislation which will extend the controls on emissions to the entire class of compounds, the saturated perhalo chlorofluorocarbons, or perhaps to the lower molecular weight members of the series, as for example to the compounds containing 3 or fewer carbon atoms. Provision has been made for the addition of compounds to the list in Annex A, Group I of the Montreal Protocol, but this may prove to be a cumbersome process. The key point is to discourage completely the release to the atmosphere of dangerous CFCs not yet on the Annex A list. (A limiting concern on the other hand is not to restrict uses which do not involve release of such compounds to the atmosphere, as might be the case with some higher molecular weight materials which do not basically exist in liquid or gaseous form. The limitation to C_3 or C_4 chlorofluorocarbons or smaller is directed toward limiting the proscription to the gaseous and volatile liquid members of the class.)

One additional compound which should probably also be seriously considered for inclusion in Annex A, Group I, is carbon tetrachloride, CCl_4. This compound (see Figures 1 and 6) was the first important man-made chlorine material added to the atmosphere in major quantities. The use of carbon tetrachloride in the United States as a cleaning solvent decreased very markedly about twenty years ago, and the general U.S. industrial consensus in the late 1970s was that very little carbon tetrachloride was now being released to the atmosphere. Its major current use is as the precursor molecule in the manufacture of CFCs, converted by fluorination into CFC-11 and CFC-12. However, measurements in the atmosphere have since established both that carbon tetrachloride is long-lived in the atmosphere (average lifetime 50 years or more), and that its concentration has been steadily increasing over the past decade. This steady increase in concentration implies release to the atmosphere in yearly amounts of 100 to 150 kilotons on a global basis. Apparently, the use of CCl_4 in processes involving its release to the atmosphere in unchanged chemical form is more prevalent in some other countries than it is currently in the U.S. The tonnage release to the atmosphere is globally significant, and carbon tetrachloride merits inclusion on the list of volatile chlorinted materials whose further release to the atmosphere should be severely restricted.

In summary, very strict control of further global emissions of long-lived organochlorine molecules to the atmosphere is imperative for the preservation of the atmosphere in its present form, and should be the concern of the U.S. Congress as well as the United Nations. Controls far more stringent than the minimums prescribed by the Montreal Protocol are completely in order. Legislation by individual nations will be very advantageous in leading the way globally in protecting the existing concentrations of stratospheric ozone. The massive losses of ozone reported over the Antarctic this year by satellite measurements and by the Punta Arenas aircraft expedition are an explicit warning that the ozone layer is exceedingly fragile, and its careful protection has become an urgent global need.

ENVIRONMENTAL DEFENSE FUND

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Testimony of Dr. Michael Oppenheimer

before the

Subcommittee on Hazardous Wastes and Toxic Substances

and

Subcommittee on Environmental Protection

Committee on Environment and Public Works

United States Senate

October 27, 1987

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My name is Dr. Michael Oppenheimer. I am an atmospheric physicist and senior scientist at the Environmental Defense Fund, a national non-profit organization. I would like to thank the committee for inviting me to testify today on the implications of Antarctic ozone depletion.

This testimony contains an interpretation of recent scientific observations, and a projection of the observations into the future. As uncertain as such projections may be, the effectively irreversible nature of ozone depletion demands that we make them. The observations lead me to conclude that current atmospheric chlorine levels present substantial risks to the environment. My specific findings are:

-- Increasing Antarctic springtime ozone depletion would not occur in the absence of emissions of halocarbon compounds such as CFC's.

-- Seasonal ozone depletion, perhaps related to depletion in the Antarctic vortex, has occured broadly in the southern half of the southern hemisphere. Ozone-poor vortex air could, depending on mixing, cause depletion outside the vortex.

-- Biological consequences of seasonally enhanced ultraviolet radiation due to ozone depletion could be affecting the Antarctic marine food web now.

-- The ozone hole will be with us for decades, although its intensity will vary, as long as chlorine concentrations remain at least at current levels. So any biological consequences of Antarctic depletion will be long lived. In general, the hole can be expected to deepen if atmospheric chlorine increases, i.e. as long as significant CFC emissions occur.

-- Growth of other greenhouse gases and of aerosol particles in the atmosphere may create conditions in the future which are favorable to enhanced ozone depletion at other latitudes, even at current chlorine levels. More in situ observations of low-altitude mid-latitude ozone chemistry are urgently needed to determine if such "fast kinetics" have already begun.

-- The ozone hole was a "surprise". It apparently results from the amplification of an atmospheric perturbation caused by 3ppb CFC levels, by interaction with a cooperative phenomenon, condensation. We should expect further, nastier surprises of this sort in the atmosphere-ocean system as long as ozone-depleting and greenhouse gas emissions grow. Earth life-support systems now appear capable of large and rapid change due to human disturbance. We must enhance our capability to predict and avoid other such surprises before their worst effects occur.

As my testimony concludes, we should take the ozone hole for a warning: even current atmospheric chlorine levels bear uncertain risk of unacceptable consequences. The only sure route to avoidance of such consequences is the rapid elimination of CFC emissions.

Lessons From The Ozone Hole

The ozone hole, discovered only recently, has already borne unprecedented consequences for human affairs. In addition to generating an intensive scientific research effort and spurring an international accord to protect the ozone layer, it has become a symbol of the unexpected consequences of unconstrained industrialization, a metaphor for global change. Large advances in a brief period have been made in understanding the physical origin of the hole; little is yet known of its biological consequences; and its implications for the future course of ozone depletion is a matter of scientific controversy. But even as research progressively clarifies these issues, it is critically important to evaluate the significance of the hole from a global viewpoint. Here I undertake a preliminary exploration of this issue by examining the properties of the ozone hole in the larger context of global atmospheric change. I will argue that it is the first manifestation of a class of phenomena which present extraordinary environmental risks.

Ozone Chemistry

The special nature of the ozone hole is readily understood from an examination of the processes which create and destroy ozone in the atmosphere. At altitudes above 20 km in the mid-latitude stratosphere, solar ultraviolet radiation causes the fragmentation of molecular oxygen into atoms. These atoms recombine with oxygen molecules to form ozone. At lower altitudes, methane and nitrogen compounds, gases whose atmospheric concentrations are increasing due to human activity, also play a minor role as a source.

Ozone is destroyed by a host of reactions. Human activity intervenes in these processes by supplying chlorine, bromine, and nitrogen compounds to the stratosphere. Human activity, through enhancement of the global greenhouse effect, also alters the stratospheric temperatures, and thereby changes the rates of ozone-destroying processes.

The largest perturbation on these natural cycles comes from the emissions of chlorofluorocarbons (CFC's), which are fragmented by ultraviolet radiation above 30 km to liberate chlorine atoms. Chlorine accelerates the natural destruction of ozone through a series of catalytic processes. Two important properties of this sequence are:

1. each chlorine atom destroys over 100,000 ozone molecules during its stratospheric life

2. this destruction efficiency would be as much as ten times higher were chlorine not sequestered as chlorine nitrate ($ClONO_2$) and hydrochloric acid (HCl)during much of its stratospheric residence, instead of in reactive forms such as chlorine monoxide (ClO.)

According to atmospheric models which rely on gas phase chemical processes, the current stratospheric chlorine levels, about 3 parts per billion, are sufficient to reduce total ozone by about one-half percent, with depletions of a few percent near 40 km partly compensated by modest increases below 20 km. Ozone depletion will increase for some time because current chlorine levels are about one-sixth of steady-state values at current emissions rates. In other words, due to the very long lifetimes of CFC's, we are adding chlorine to the atmosphere much faster than it is being removed. Detailed calculations show that:

3. other things, such as atmospheric temperature, being equal, ozone depletion will increase for decades at today's emission rates, or even at half those values. An 85 percent emissions reduction, however, would bring near-term stability to the ozone layer.

The existing atmospheric load of chlorofluorocarbons would decrease very slowly, even if emissions were reduced to zero immediately, with about one-third of CFC-11 and CFC-12 remaining after 65 and 130 years, respectively. In the time frame of a few decades, we conclude that:

4. ozone depletion is effectively irreversible.

Given these properties, the origin and future course of the ozone hole may be understood, if only with limited confidence.

Formation of the Ozone Hole

The ozone hole refers to the depletion of stratospheric ozone between 12 and 20 km altitude over Antarctica. The depletion begins in August, and diminishes in November, with minimum ozone values observed in October. Depletion has increased over the last decade to a total ozone loss of one half in 1987, with higher loss at particular altitudes.

The ozone hole arises from special conditions in the Antarctic stratosphere which increase the availablitiy of active chlorine which destroys ozone, while preventing the replenishment of the depleted ozone stock. The hole occurs within the Antarctic circumpolar vortex, a winter and early springtime pattern of atmospheric circulation which virtually isolates much of the air above that continent from the rest of the atmosphere. Within the vortex temperatures in the lower stratosphere are extremely low, climbing from below -80C in mid August to more normal stratospheric values of -40C by November. At the lower temperatures, moisture condenses into droplets forming polar stratospheric clouds. These droplets provide surfaces which facilitate the formation of nitric acid, which also condenses into cloud droplets. Once nitrate is sequestered as nitric acid in droplets, it cannot combine with chlorine to form $ClONO_2$. Therefore, a higher fraction of chlorine is free to destroy ozone. Chemical reactions, perhaps occuring on surfaces, may free chlorine from HCl at the same time. Once the sun rises sufficiently to free chlorine from its various inert over-winter forms (such as HOCl), ozone depletion proceeds rapidly, at about one percent per day. We may conclude that:

5. low temperatures and the availability of surfaces for reaction speed ozone depletion in the Antarctic vortex. The general increase of springtime depletion over the last decase is a reflection of increasing atmospheric chlorine levels.

Increasing depletion would not occur in the absence of halogen compounds such as CFC's. The resulting depletions might still be relatively modest were it not for the low sun angle of the early Antarctic spring, along with the isolation of the vortex. The former prevents formation of fresh ozone from oxygen, while the latter prevents mixing with ozone-rich air from more northerly latitudes. The ozone decline continues until November when the stable vortex pattern breaks up. Bromine may play a special role in the vortex by facilitating the catalytic chlorine cycle under low-uv conditions.

Not only does the ozone hole arise from a combination of unusual circumstances peculiar to Antarctica, but the climatological conditions may have been somewhat unusual in the Antarctic stratosphere over the last few years at least. A progressive cooling of the stratosphere and a lengthening of the vortex duration have been observed. Some have suggested that the depletion of ozone itself, by removing a heat source, has cooled the stratosphere. This chicken-and-egg problem remains to be resolved, but it is important to note that the large current depletions may come and go with climatological changes. That the depletion is at least modulated by such variation is clear from the biennial oscillation in depletion which has been ascribed to planetary wave shifts. It has also been suggested that increasing greenhouse gas concentrations may have begun to cool the stratosphere, in which case conditions may become increasingly favorable for depletion.

A final observation bears on our discussion. Total ozone has decreased not just over Antarctica, but over the entire region south of about 45°S during springtime. This extra-vortex depletion, while not caused by local chemistry, could result from mixing with ozone-poor vortex air. Alternatively, the peculiar climatological conditions leading to the recent cooling and stabilization of the vortex could be responsible by dynamically shifting ozone about the hemisphere. This phenomenon is particularly disturbing since populated areas now sit beneath a 15 percent ozone depletion relative to pre-1979 values, during spring (and possibly beneath a smaller depletion over a longer time). This concern is temporarily moderated by the fact that an ozone bulge exists at these latitudes under normal circumstances. But the fact that ozone-poor vortex air could, depending on mixing, cause depletion outside the vortex is of considerable concern.

Biological Consequences

The ozone hole is sometimes viewed as a harmless accident which provides a vivid lesson on the potential consequences of unconstrained CFC emissions, but at no real environmental cost. Unfortunately, this view can be sustained only by disregarding the rich coastal and marine environment which thrives in and near Antarctica. The marine food web, which supports krill, whales, seals, penguins, and other birds, rests on a planktonic base which may in fact be quite vulnerable to changes in ultraviolet radiation. Experiments performed in the early 1960's, by Goldman and co-workers, indicate that primary productivity, at least in freshwater Antartctic phytoplankton, is surpressed by increased exposure to light. Recent laboratory studies indicate that increased ultraviolet exposure limits zooplankton productivity under controlled conditions. The ultraviolet increase accompanying the springtime depletion is small in absolute size due to the low solar angle, but high in relative amount, up to a factor of two. Whether such changes are sufficient to damage or surpress marine organisms is under study now by two expeditions sponsored by the NSF. As discussed later, one can only hope that such damage is not occuring because the ozone hole will apparently be with us, at least sporadically, for the better part of a century.

Another possible set of biological impacts arises from the exposure of human populations in South America to enhanced ultraviolet levels. As noted earlier, a substantial fractional depletion occurs over southern Argentina and Chile during the hole formation period. The relation of this phenomenon to the vortex is unclear, but it could mean that populations are temporarily exposed to higher levels of ultraviolet radiation than they would otherwise experience in absence of CFC's.

Policy-related Scientific Issues Raised by the Ozone Hole

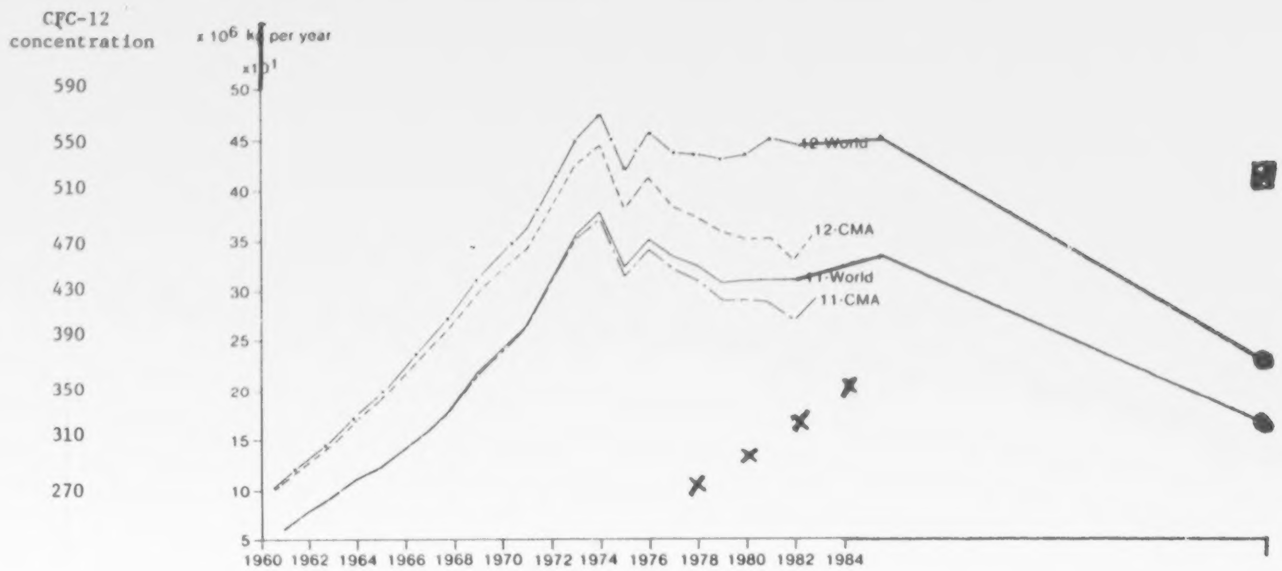
If the ozone hole has implications for public policy, in addition to the concerns for the Antarctic marine environment, they arise from two questions:

- -- Will the Antartic depletion deepen or affect a larger area in the future?
- -- Does the depletion in the vortex indicate that rapid depletion can occur now or in the future at other locations?

Implications for Other Times

These questions can now be addressed given the preceeding outline of the origins of the ozone hole. With regard to the first issue it appears that as long as the chlorine, and perhaps the bromine, concentrations in the atmosphere increase, so will depletion on a long term, average basis, in the hole. Since this depletion appears to be modulated at least bienially and

Figure 1



CFC-11 and CFC-12 emission and concentration through the year 2000.

The pre-1985 figure is taken from Gamlen et. al. (Atmospheric Environment, 20, 1077, 1986). The post-1985 emissions trajectory is schematic and does not attempt to reflect intermediate reductions before 2000 in a discrete manner. Furthermore, the attainment assumptions are optimistic in that no growth in LCC's is assumed and slightly higher than mandated penetration of alternatives in developed countries is assumed. Note that more than 50 percent as much CFC-11 & 12 will be added to the atmosphere in the next 12 years as in all previous time.

X refers to CFC-12 concentrations in the atmosphere. The year 2000 point, $\boxed{X}$, is derived from the emissions projections.

perhaps over longer periods, by dynamical shifts in the atmosphere, the amount of depletion may vary from year to year, and it cannot be excluded that the hole will effectively disappear at some point. But as long as halogen atoms are present in the stratosphere near current levels, it will surely return.

The reasons for this continuing growth of the hole are clear from figure 1, where we have plotted CFC emissions over time. Atmospheric chlorine concentrations are also exhibited. Future emissions are based on an optimistic projection of the consequences of the recent ozone accord. In spite of the projected decline in emissions, atmospheric chlorine concentrations will continue to increase. With chlorine continuing to accumulate in the atmosphere, ozone depletion can be expected to increase.

6. On a long-term average basis, a continued decline in Antarctic ozone can be anticipated until emissions are reduced to about 15% of current values, when atmospheric chlorine will not longer increase.

With regard to the ozone hole there is probably a geographical limit to large fractional depletion because the chemical-activity region is limited by dynamical and thermal considerations; and, with some layers in the vortex already very highly depleted, there is less and less ozone left to remove.

However, as we have discussed, the mixing of ozone-poor vortex air into more northerly latitudes may be causing ozone depletion up to 45°S. Therfore:

7. Ozone depletion in the Southern Hemisphere outside the vortex may continue to increase as the ozone hole is deepened by added chlorine.

Implications for Other Places

The implictions of the ozone hole for ozone at other locations is the most important issue from a policy perspective. Needless to say, depletions of the magnitude observed in Antarctica could not be tolerated at populated latitudes (and may be intolerable from a biological viewpiont even in Antartica). To place them in context, the ozone protocol was negotiated to a target depletion of about one percent at mid-latitudes.

The dependence of the Antarctic depletion on the special physical context of the vortex does not mean that it bears no implications for other latitudes. As C. B. Farmer has noted, the vortex is like a reaction vessel where the conditions for catalytic removal of ozone have been optimized. It provides a clear test, with a positive result, of the theory that chlorofluorocarbon emissions can cause ozone depletion. Can such an optimization of conditons, perhaps to a lesser extent, occur elsewhere, now or in the future?

Role of Stratospheric Aerosol Particles

The Antarctic observations suggest that surface reactions on cloud droplets may play a role in accelerating ozone depletion. Aerosol particles, which are droplets of a different composition, primarily condensed sulfuric acid, are widespread in the mid-latitude stratosphere between about 20 and 30 km. These particles could provide surfaces for reactions which free chlorine from its HCl and $ClONO_2$ reservoirs. Laboratory experiments are now underway to test this hypothesis. Model simulations indicate that if such reactions are rapid, they could accelerate depletion to a current value of a few percent, as opposed to less than one-half percent in models which ignore these reactions. Curiously, some analyses of historical ozone trends (such as those inferred from SBUV data) suggest a recent decrease by roughly this amount. If these reactions are indeed important, the projections on which the protocol are based could be under the mark by a factor of five to ten.

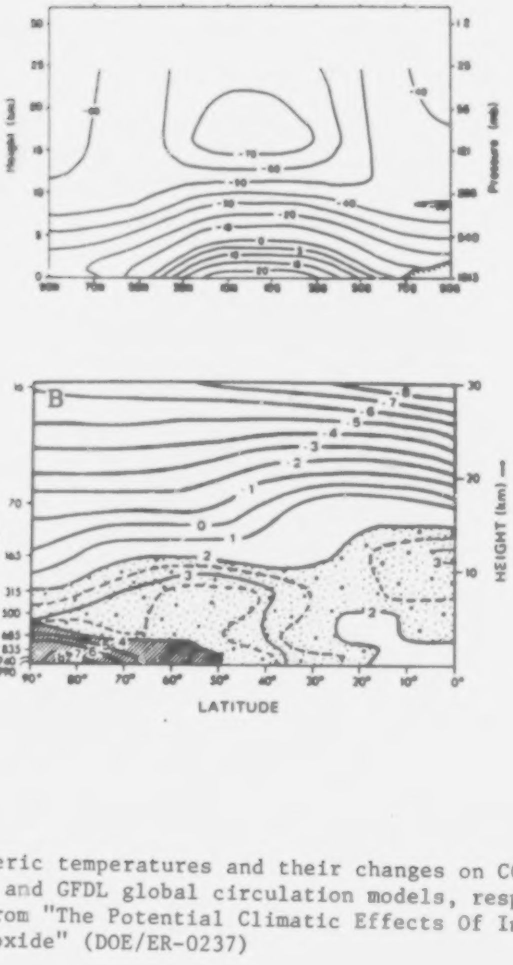
The potential growth of these particle concentrations in the atmosphere is a cause for additional concern. These particles originate in volcanic emissions of sulfur dioxide, direct and indirect biotic emissions of carbonyl sulfide and carbon disulfide, and industrial emissions of these last two chemicals. The very spotty data available (only 3 points) suggests that non-volcanic aerosol concentrations have indeed been growing for three decades. Such growth could be attributed to fossil fuel use and human disturbances of the natural environment. To the extent that increases result from biotic sources, they will be accelerated by anticipated climate warming accompanying the greenhouse effect.

8. Aerosol particles could be causing a faster-than-predicted depletion at midlatitudes. The sources of aerosol are increasing due to human activity. It is critically important that aircraft and laboratory studies of these processes be accelerated.

The Greenhouse Effect and the Fate of the Ozone Layer

In the context of gas phase models, lower temperatures slow ozone depletion by retarding the ozone destroying reactions. But the low temperatures of the vortex speed the depletion of ozone by causing condensation of nitric acid, or by providing droplet surfaces for $ClONO_2$ and HCl disruption. Temperatures sufficiently low to replicate these conditions, at least in a limited way, may currently exist in the north polar regions where seasonal depression of ozone has been noted over Alert at 83° N. Thus the response of ozone to any potential stratospheric cooling is problematic. Of considerable concern, therefore, is the fate of the ozone layer as the global greenhouse effect increases due to carbon dioxide and other trace gas emissions. The greenhouse effect will warm the surface but cool the stratosphere above about 18 km due to

Figure 2



Stratospheric temperatures and their changes on CO_2 doubling from GISS and GFDL global circulation models, respectively. Figures from "The Potential Climatic Effects Of Increasing Carbon Dioxide" (DOE/ER-0237) trapping of heat from the surface at lower altitudes. The degree of cooling is uncertain, but even a few degrees at tropical latitudes, where temperatures in the stratosphere are already low, could precipitate conditions not dissimilar to those inside the vortex. For comparision, model values of stratospheric temperatures under current conditions and decreases projected for enhanced greenhouse conditions are presented in Figure 2.

The troubling aspect of this analysis is that relatively low chlorine abundances could cause substantial ozone depletion if a stratospheric cooling occurs, much as current chlorine concentrations caused large Antarctic depletion. Furthermore, the projected growth in aerosol could act synergistically with lower temperatures since increased aerosol may provide nuclei for increase numbers of cloud droplets, and thus enhance surface reaction rates.

9. Stratospheric cooling accompanying the enhanced greenhouse effect may create conditions increasingly optimal for ozone depletion, even at current chlorine concentrations.

Surprise, Risk, and Decision

The ozone hole is an excellent example of a surprise occurrence in the environment. Folllowing C.S. Hollings' definition, surprise connotes the qualitative deviation of perceived reality from expectation, not just a numerical error in prediction. In the case of the ozone hole, the surprise is reflected in the rapid, local, non-equilibrium loss of ozone. This behavior, in turn, reflects the importance of condensed states of matter as either sinks for nitrogen compounds, surfaces for rapid reactions, or both. The ozone hole arises because a process which is usually a small perturbation on atmospheric concentrations becomes coupled with a cooperative process, condensation. Such processes radically alter the conditions in the gas, changing the otherwise slow process into a very rapid one.

Scientists did not predict the ozone hole phenomenon, but perhaps they could have. All the elements individually were recognized. Low-nitrogen conditions (relative to chlorine) were predicted to amplify ozone depletion; the potential role of surface reactions had been explored in the context of atmospheric ozone chemistry; low temperatures were known to exist in the Antarctic stratosphere; polar stratospheric clouds had been discovered a few years earlier; and direct evidence of the hole lay unappreciated in data archives.

This experience provides an important lesson with regard to the risks we take in modifying the atmosphere: our predictive capability is poor when dealing with conditions far from the normal atmospheric equilibrium. This finding is not particularly startling, but it has important implications. For instance, even low levels of atmospheric trace gases could prove highly problematic if the condensation conditions in the atmosphere change. Since small changes in temperature and continued particulate loading promise just such alterations, it appears that we are currently venturing into unchartered and highly risk-laden territory. We ought to be extremely skeptical of our predictive capabilities, and we ought to expect other nasty surprises.

These changes in the state of the atmosphere may be brought about by continued emissions of greenhouse gases, such as CO_2 and CFC's, and by the continued destruction of ozone which also alters the atmosphere's thermal balance. Human activities which alter the stratospheric aerosol burden are also of concern.

From a policy viewpoint, the singular property of CFC's and most of the other greenhouse and ozone-altering gases is that their atmospheric concentrations are not easily altered in the downward direction after emission. The very long lifetimes of CFC's noted above are dwarfed by the stability of the atmospheric CO_2 pool. Even if CO_2 emissions ceased today, preindustrial levels would not be attained again for 1000 years unless extraordinary efforts at re-forestation were undertaken. Nitrous oxide also has a very long atmospheric lifetime. Of the major greenhouse gases, only methane and ground level ozone can decrease rapidly.

10. Once the suite of atmospheric trace gases is altered, we cannot quickly retrace our steps, and we are left with the consequences for a very long time.

The risk of large scale future ozone depletion carries with it the risk of unacceptable biological consequences. The predicted affect of even a small depletion from standard gas phase processes, on the order of two percent globally, was a large increase in skin cancer incidence, costly damage to crops, and uncertain alterations to natural ecosystems. It is worth noting that if the ozone trend noted in SBUV data is confirmed, and if it results from accelerated ozone depletion at midlatitudes due to surface-CFC chemistry, we may have already exceeded the damage targets which the ozone protocol sought to avoid.

11. Since even current atmospheric CFC levels may prove dangerous in the future, and the consequences are unprecedented and effectively irreversible, the only sound management strategy for the ozone layer is the rapid elimination of CFC emissions.

Lessons for the Global System

The lesson on surprise can be tentatively extended to other parts of the global system. The ozone layer is part of the coupled ocean-atmosphere system. Cooperative phenomena, which may give rise to radically different system states, are an integral component of the mass and energy flow mechanisms in the system. We are quite used to living in one state of this system, and quite unused to any other. Broecker has noted the potential for rapid changes in the state of the ocean-climate circulation system in a recent Nature article. The ozone hole demonstrates that large and rapid changes to parts of global systems do occur. A surprise in the ocean circulation system has consequences which dwarf those of the ozone hole.

An important question is whether there is any chance to predict such surprises. From a policy perspective in the context of climate change, such predictive power has important implictions since a convincing demonstration of the rather slow climate change will be difficult until a large atmospheric commitment to climate warming is built up in the form of emitted greenhouse gases. In contrast, surprises by their very nature grab the attention of public and policy makers. The ozone accord may not have been completed without the ozone hole appearance, for instance. Unfortunately, the impetus for dealing with climate change may only come after the eventuation of such a surprise, and it will have meaning for decision makers only if it is either predicted or quickly interpreted. The cooperative systems in the atmosphere, the oceans, and in terrestrial ecosystems, are natural places to examine for the potential for surprise.

Making the Protocol Work

The note of urgency in this analysis with regard to CFC reductions should not be taken as a criticism of the ozone protocol recently signed in Montreal. Rather, it should be viewed as a call to pursue the protocol's mechanisms to the fullest to assure the rapid elimination of CFC emissions. The 50 percent reduction is not to be viewed as an endpoint but rather a mechanism for initiating the process of eliminating ozone-depleting CFC's. Among the important steps for action over the next two years by the U.S. government are:

-- assure approval of the accord by as many nations as possible, as soon as possible

-- Secure meaningful trade sanctions on highly visible items such as automobiles and computers when CFC's enter into manufacture

-- Insist on a rapid scientific review and revisitation of the schedule for reductions based on recent Antarctic findings. Twenty percent global reduction is possible immediately, and another 40% or more within 5-7 years.

-- Assure a strong domestic response, including incentives for investment in research on alternatives, and assistance for user adaptation

Other Lessons

Because the ozone hole may be with us for decades, it provides unique opportunities for scientific observation: a single perturbation in the form of enhanced ultraviolet flux imposed on an otherwise pristine ecosystem presents unusual opportunites. But beyond these scientific ventures, the learning experience, not just for scientists, but for policy makers and the general public is unique. If we should be so fortunate that the ozone hole does not generally affect southern hemisphere ozone, and that it is not severely damaging the Antarctic ecosystem, then its symbolic value may in the end override its damaging consequences. The appearance of the hole was probably the most important factor in moving nations in Europe to agree on the ozone protocol. It may stand for decades as a red light flashing a warning every spring against too much tampering with the natural world. We should not fail to heed it.

STATEMENT FOR THE RECORD
OF
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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

BEFORE THE

SUBCOMMITTEE ON HAZARDOUS WASTES AND TOXIC SUBSTANCES
SUBCOMMITTEE ON ENVIRONMENTAL PROTECTION
COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS
UNITED STATES SENATE

OCTOBER 27, 1987

Mr. Chairman and Members of the Subcommittees:

My name is Daniel L. Albritton. I am Director of NOAA's Aeronomy Laboratory in Boulder, Colorado, which studies the chemistry and dynamics of the atmosphere. I appreciate this opportunity to submit written testimony to your Subcommittees on the subject of stratospheric ozone. My comments here will be in the context of the following background.

BACKGROUND

Reemergence of the Ozone/Chlorine Issue

As you well know, the issue of stratospheric ozone depletion by man-made chlorinated compounds was first raised in 1974. Shortly thereafter, the United States banned the sale of these chemicals in aerosol spray cans, since a thinner ozone layer would imply an increase of harmful ultraviolet radiation at the Earth's surface. This ban marked a peak in the worldwide production of these compounds, and the late 1970's and early 1980's saw a slow decline in their usage. Stratospheric ozone research continued, but out of the lime light, which was occupied by new atmospheric environmental issues, such as acid rain. A major emphasis in stratospheric research during this period was the building of a better theoretical understanding of stratospheric processes and a testing of that understanding by improved observations.

Yet, in the last year or so, stratospheric ozone has been thrust back into the spotlight within both atmospheric science and public policy. Why this reemergence of the ozone layer as an issue after a decade of semi-retirement from the public eye? The reasons are severalfold, the major ones being the following:

- Over the past few years, the worldwide production of chlorinated compounds has begun to increase once again.
- Ozone/chlorine theory suggests that, if such chlorinated emissions continue to increase indefinitely, the predicted current global column-ozone depletion of less than 1% would very likely grow to several percent in the next century, particularly at high latitudes.
- The research of the past decade has increased substantially the confidence in this theory and hence the predictions made with it.
- The "greenhouse" role of the chlorinated compounds has been recognized; namely, they contribute to a warming of the Earth's surface in the same manner as does carbon dioxide.

- The usage and hence the atmospheric abundance of brominated chemicals are now increasing, and bromine is several times more effective than chlorine in destroying ozone.

The technical and scientific community broadly supports the validity of these five points. Hence, their implications have sounded a call for new action. That call was answered with an unprecedented recent international accord regarding these halogenated (i.e., chlorinated and brominated) compounds.

The Montreal Protocol

On Wednesday, 16 September 1987, the United Nations adopted the "Montreal Protocol on Substances That Deplete the Ozone Layer". This adoption was preceded by several months of intense international and domestic debate on relevant scientific, technical, legal, and diplomatic points. It is not the purpose of my testimony to summarize the twists and turns of that course or the provisions of the Protocol. Others at this hearing can do it better than I.

It suffices here to note that the Protocol calls for (a) an early freeze on the usage of key chlorinated compounds, (b) a phased reduction in their usage leading to an eventual 50% decrease, (c) an evaluation in 1990 of whether more or less reduction is deemed appropriate, and (d) a similar, but delayed, schedule for the brominated compounds. An international scientific assessment is planned for 1989 so that this guidance would be available as one of the inputs to the 1990 policy review.

Other Ozone-Science/Public-Policy Issues

The five points noted above are the scientific pillars on which the Montreal Protocol rests. The maturity of the theory and the unambiguity of the observations were obviously as convincing to the diplomatic community as they were to a large majority of the scientific community. There are, however, other ozone/chlorine topics that were certainly identified in advance of the Protocol debates, but did not play a direct role because generally accepted conclusions had not yet been reached by the scientific community. Two of these are noteworthy:

- Preliminary data from the Solar Backscatter Ultraviolet (SBUV) satellite instrument, if taken at face value, show large declines in global ozone since 1979. A small minority of the scientific community interpreted this decrease as being due to ozone destruction by chlorine compounds.

- The discovery of a large (50%) seasonal decrease in ozone over Antarctica was reported in 1985. Initial explanations of this remarkable phenomenon included both natural and man-made causes. Field measurements in Antarctica during August and September of 1985 found perturbed chemistry that was consistent with, but not proof of, ozone loss due to chlorinated compounds.

There is little doubt that these topics, despite their incompleteness, provided some of the impetus to move toward the Montreal Protocol, particularly the dramatic Antarctic "ozone hole". However, since research has continued unabated on both of these topics, their importance lies not in the past, but rather to the present and to 1988, when the ratification and the provisions of the Protocol will be under extensive discussion.

It is worth emphasizing the important issues associated with both of these topics. First, _if_ the reputed ozone decreases from SBUV are indeed (a) correct and (b) due to chlorine, then something would be seriously amiss with current theory, which predicts present global losses due to chlorine as being less than a percent. Second, _if_ the "ozone hole" is indeed due to chlorine, then the evidence for the first massive manmade perturbation of the ozone layer would be upon us now, not off in the distant future.

The Present Testimony

NOAA and its scientists have devoted considerable time over the past decades to ozone research. The level of this has increased in recent years. For example, NOAA investigators served as the Mission Scientists for the interagency 1986 and 1987 ground-based National Ozone Expeditions and the 1987 Airborne Antarctic Ozone Campaign. In addition, a substantial number of NOAA scientists and engineers joined their colleagues from the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), universities and institutions abroad to make up the teams of both of those expeditions, as well as other research projects. Furthermore, NOAA joined with NASA to provide scientific advice to the U.S. delegation that worked toward the Montreal Protocol. Therefore, I am pleased to represent the efforts of all those NOAA scientists and to address the following topics in this testimony:

- What is the current status of the scientific understanding of (a) global ozone and (b) Antarctic ozone?
- What additional scientific information is likely to be forthcoming in 1988 and 1989 that could be relevant to public policy?

STATUS OF THE SCIENCE: GLOBAL OZONE

This summary seeks to give the current answers to the following two questions:

- What does our present theoretical understanding of stratospheric processes predict for the present and future global ozone response to chlorine emissions?
- Do ozone observations reveal any evidence that ozone has been lost on a global scale due to past chlorine emissions?

Theory: Background

- From a scientific perspective, any regulatory policy should consider all of the fully halogenated compounds, which are characterized by high ozone depleting potentials and long atmospheric lifetimes, as a group for the purposes of regulation. The Montreal Protocol indeed includes all of the currently important fully halogenated chlorofluorocarbons (CFC's) and brominated compounds (Halons).

- Several chemical compounds that have low ozone depleting potentials may have significant value as possible future substitutes. The Montreal Protocol indeed does not prohibit the use of these possible substitutes.

- The fully halogenated compounds have long atmospheric lifetimes; therefore, their stratospheric abundance would continue to grow for many decades, even if their emissions were to plateau or decrease moderately. Hence, from the standpoint of limiting the maximum concentrations of chlorine and bromine in the stratosphere, emission-rate restrictions done earlier need not be as severe as those done much later. This is consistent with the Montreal Protocols's attempt to get a "freeze" on emissions as early as possible.

- o The current understanding of stratospheric chemistry and circulation predicts that the halogenated compounds will alter the:
  - total column amount of ozone overhead,
  - variation of this column ozone with latitude, and
  - vertical distribution of ozone.
- o The response of stratospheric ozone to emissions of halogenated compounds is sensitive to the atmospheric growth rates of other trace gases, such as carbon dioxide, methane, and nitrous oxide, which are emitted from man-made and natural sources.

Theory: Predictions

- o Policy has not set a "tolerable" stratospheric ozone loss. Therefore, as an aid to judging the significance of a possible ozone loss, each of the following predictions are compared to the best estimates of natural variability.

Global-average column ozone

- o Model predictions for all scenarios that include continued growth of the emissions of the halogenated compounds at current rates or greater show global-average column ozone losses in the next century that are larger than or equal to observed natural ozone decadal variability, which is about 3 to 4%.

- Hence, a true global freeze of the sum of the chlorine and bromine reaching the stratosphere to current rates is consistent with limiting predicted long-term perturbations in the global-average column ozone to magnitudes less than the decadal natural variation.

- This prediction (as well as the ones below) assumes continual current percentage growth in carbon dioxide and methane. If less growth actually occurs, then more column ozone depletion is predicted; if more growth occurs, less column ozone depletion is predicted.

High-latitude column ozone

- The current understanding of the interaction of stratospheric circulation patterns and ozone-loss chemistry predicts that more column ozone loss will occur at higher latitudes than at the equator.

- Hence, a significant decrease in total chlorine and bromine emission rates is consistent with limiting predicted long-term perturbations in the column ozone at high latitudes to magnitudes less than decadal natural variation.

Upper-stratospheric ozone

- Even with a true global freeze, current theory predicts substantial long-term losses of ozone at 40 km, which may alter stratospheric circulation patterns because of the accompanying cooling.

- Hence, a significant decrease in total chlorine and bromine emission rates is consistent with limiting predicted long-term losses in the ozone at 40 km and associated decreases in local temperatures to magnitudes less than the current (limited) observations of decadal natural variation, which is about 1 to 2C.

- However, the couplings and feedbacks of chemistry, radiation, and circulation in the upper stratosphere have yet to be represented fully in three-dimensional models. Furthermore, the possible effects of the predicted upper-stratospheric cooling on life at the Earth's surface are unknown at present.

Greenhouse effect

- In addition to their relation to stratospheric ozone, many of the halogenated compounds absorb infrared radiation and hence contribute to the "greenhouse" effect, which elevates surface temperatures.

- A decrease in the total emission rates of halogenated compounds appears to be consistent with limiting their predicted commitment to a long-term "greenhouse" warming such that it is less than the decadal natural variation, which is about 0.5C.

Uncertainties in the Theory:

- All of the above ozone responses are predictions made by atmospheric models that are based on the current understanding of the relevant atmospheric processes.

- While these models indeed simulate much of the present atmosphere very well, they are not perfect, which places a factor of two to three uncertainty on their predictive abilities.

- Since stratospheric ozone is sensitive to changes in other trace gases, an additional uncertainty is the difficulty in predicting their future abundances, particularly those of carbon dioxide and methane.

- Nevertheless, most atmospheric scientists believe that if the present growth rates of chlorinated and brominated compounds continue unabated indefinitely, then it is highly likely that substantial global ozone depletions will occur in the next century, particularly at the higher altitudes and latitudes. This belief is consistent with a key initial goal of the Montreal Protocol: to limit the future abundances of chlorine and bromine in the stratosphere.

Three "standard" emission scenarios were cited in the above points: (a) continued growth of emissions, (b) a true global freeze (i.e., a constant annual amount of chlorine entering the stratosphere, and

(c) a diminishing annual amount of chlorine entering the stratosphere. Which one is the Montreal Protocol likely to yield? Obviously, the goal is (c).

It is presently an open question as to what the emissions will be over the next decade if the Protocol is ratified by a substantial number of countries. The reason for this current uncertainty is that the Protocol's provisions will guide directly only the signers, and hence it is possible to determine accurately only that fraction of the total worldwide emissions. Yet, it is certainly important to get the best estimate of what the total worldwide emissions might be. Only then can one make the calculation of the likely ozone depletion that would follow the adoption of the Montreal Protocol.

Unfortunately, it is a calculation that cannot be done currently with high confidence. Let me explain why. To my knowledge, there does not exist a generally accepted estimate of the likely emissions from non-signers, less-developed countries, or non-compliers. It is possible that the Protocol's freeze-plus-20% provisions will yield something close to the true global freeze defined above. If so, the above prediction associated with that "standard" scenario would be the appropriate one. But this can only be speculation at present.

The importance of a carefully done, independently-reviewed analysis of the likely emissions due to non-signers and others is quite clear, since it will be a key factor in the 1988 and subsequent analyses of the adequacy of the Protocol's provisions for protecting the ozone layer. For example, the calculations at the UNEP-sponsored Wurzburg meeting (UNEP/WG.167/INF.1, 31 pages, 10 April 1987) used assumed sets of simulated-Protocol emission reductions and non-signer emission increases. It was noted that, with an assumed set of high emission increases for non-signers, the simulated-Protocol emission reductions would have to be huge to come even close to the ozone protection characteristic, for example, of a true global freeze situation. However, there was not consensus on the realism of the assumed large non-signer emission increases.

Therefore, there is a clear need for those who are skilled and experienced in estimating the demographic, economic, and industrial factors in chlorine production and usage to formulate an estimated set of emissions and accompanying uncertainty bounds. Those skills do not reside in NOAA, which has focused on understanding the atmospheric response to emissions, rather than research on emission estimates themselves.

Ozone Trends and Interpretations:

- The ground-based "Dobson" spectrophotometer network provides a 25-year record of global-average column ozone, which increased a few percent in the 1960's, remained relatively invariant in the 1970's, and decreased afterwards. Attention has focused on this recent 4-5% decrease because (a) it is the most-rapid sustained change ever observed in global column ozone and (b) it has occurred during the period of increasing stratospheric chlorine abundances.

- The causes of the decrease are not yet known. Solar variability, volcanic aerosols, and general circulation changes are possible contributing natural mechanisms. Indeed, past analyses of solar activity find no fully convincing statistical evidence of a human-caused depletion in global column ozone in recent years, which is consistent with theoretical predictions that current losses should be less than a percent.

- The "Umkehr" technique, which uses the Dobson instruments, yields an 18-year record of the vertical distribution of ozone. Over the past decade, the data suggest ozone decreases at the higher altitudes (and only there) that are remarkably close to model-predicted chlorine-induced depletions. However, questions about artifacts due to volcanic dust, particularly since the 1982 eruption of El Chichon, prevent a definitive statement regarding the significance of the trend.

- Unpublished results from the SBUV-1 instrument on the NIMBUS 7 research satellite apparently show distinct ozone decreases over the past eight years, both in the global column and in the upper-stratospheric abundances, that are substantially larger than those of the Dobson and Umkehr data or the theoretical predictions. However, this analysis and the calibrations are undergoing intensive review, and the results are not yet accepted by the scientific community.

- Therefore, inconsistencies between parts of the data sets and the possibility of instrumental artifacts have divided the atmospheric science community, and there is presently no universal agreement on whether there is evidence of a chlorine-induced depletion in global ozone.

These conflicting data sets are being re-examined currently. Specifically, scientists from NASA, NOAA, universities, and industry are conducting an independent evaluation of the existing Dobson, Umkehr, and satellite data sets. The goal is to address the inconsistencies, re-analyze data, intercompare in detail, re-estimate uncertainties, and put together, insofar as possible, a consistent picture of global ozone trends and their implications in a report required by section 156(a) of the Clean Air Act due by early 1988. The significance of this re-examination to policy decisions in 1988 and thereafter will be noted below.

STATUS OF THE SCIENCE: ANTARCTIC OZONE

Background

In contrast to the search for the small beginnings of the predicted global chlorine-induced ozone loss and the debate over its reality, an unprecedented and unanticipated phenomenon was discovered recently that has riveted the attention of ozone scientists, policy makers, industrialists, and environmentalists alike, namely the Antarctic "ozone hole". Here, the amount lost is considerable -- for a period in the Antarctic spring, half of the ozone over Antarctica disappears or fails to appear in a very puzzling fashion. The past chronology of the unfolding science of the "ozone hole" is as follows:

July, 1985 - Discovery: The British Antarctic survey reported that, at their Halley Bay Station, in the Antarctic spring (and only there and only at that season), a substantial fraction of the column ozone disappears. The fractional decrease has increased, on the average, over the past several years. Could it be an instrumental artifact or a local Halley Bay phenomenon?

December, 1985 - Confirmation: Other data sets were searched for the appearance of this phenomenon. The agreement between the ground-based, satellite, and balloon-borne ozone data for that region leave no doubt about the reality of this phenomenon, as well as its continental-wide extent. The magnitude of the decrease and the nature of its occurrence could not be explained by previously existing ozone-loss theory. The fact that nothing of this magnitude had occurred earlier in the south polar latitudes is shown by the 25-year column ozone record from the Dobson instruments. Indeed, this recent decrease in Antarctic ozone discovered by the British Antarctic Survey is far larger than the variability observed at any time anywhere on the globe. Hence, the ozone-science community knew that it was faced with a major question: What is causing it?

Spring 1986 - Theories: Three explanations were postulated:

- Halogen/chemical - Ice particles form in the Antarctic stratosphere because of the uniquely cold temperatures there. Chemical reactions on the ice surfaces enhance the abundance of reactive chlorine compounds, which photochemically depletes the ozone when sunlight arrives in the Antarctic spring.
- Sunspot-induced/chemical - Enhanced sunspot activity increases the abundance of naturally-occurring reactive nitrogen compounds, which also can photochemically deplete ozone.
- Dynamical/climate change - Changing climatic and circulation patterns in the southern hemisphere imply that less ozone has been transported from the tropics (where the bulk of the Earth's ozone is produced) to Antarctic. Thus, the lower ozone levels are a failing transportation process, rather than an increasing destruction mechanism.

Scientists generally agreed that the "ozone hole" ends each year by the mixing in of ozone-rich air from northward latitudes, whose transport was stimulated by the warming of Antarctica as southern-hemisphere summer advanced. However, it is noteworthy that the three theories postulate distinctly different causes. The first evokes man-made perturbations, the latter two evoke natural processes. Which one (or ones) is correct?

Summer, 1986 - First ground-based expedition. The ozone-science community was clearly faced with a data-short situation. In response, NSF, NASA, NOAA, and the Chemical Manufacturer's Association (CMA) sponsored the first National Ozone Expedition which, because of the short time available, took existing apparatus to the NSF's McMurdo Station in Antarctica. Two months of highly successful observations revealed considerable detail about the "ozone hole". The ozone losses were occurring in the lower stratosphere. The chlorine and nitrogen chemistry were strongly perturbed compared to elsewhere. The conclusions were the following. The low reactive nitrogen levels and the lower-stratospheric ozone loss implied that the sunspot theory was unlikely. The high reactive chlorine levels were consistent with (but not yet proof of) the chlorine theory. Little could be said one way or another regarding the climate change theory since these measurements primarily addressed the chemical state of the Antarctic stratosphere.

Summer, 1987 - Airborne and ground-based campaigns. Instrumented aircraft were used to probe the stratosphere where the ozone losses were occurring. Full meteorological analyses were available to assist planning the flight tracks and to define air motions over Antarctica. Balloon-borne ozonesondes were launched in concert. Satellite overpasses were available daily to reveal the spatial extent of the "ozone hole". A second, more-extensive ground-based expedition returned to McMurdo base. These long-term measurements provided a continuous and detailed record of the "ozone hole". Meanwhile, theoretical developments continued apace. In short, one of the most complex pair of chemical and dynamical field campaigns ever mounted and intense theoretical developments have substantially enhanced the understanding of the cause of the "ozone hole", as well as serving as a model of interagency cooperation.

Current Understanding

Based on the preliminary findings of the scientists involved, a provisional picture of the Antarctic ozone phenomenon is emerging. Its main features are as follows:

- o The "ozone hole" is a re-occurring phenomenon whose intensity is increasing with possibly a two-year modulation. The 1987 occurrence was the largest observed ozone decrease.
- o The weight of evidence strongly suggests that both chemical and meteorological mechanisms perturb the ozone

and that meteorology sets up the special conditions for the perturbed chemistry.

- The evidence for chemical destruction of ozone were (a) an increase in the abundance of the key reactive chlorine species - chlorine monoxide - within the ozone hole as it deepened over the observation period, (b) a growing anticorrelation between ozone and chlorine monoxide on both large and small spatial scales within the "ozone hole" as the weeks passed, and (c) no similar behavior outside of the "ozone hole".

- The evidence for the meteorological role in the formation of the "ozone hole" is the following. Rapid, large-scale changes in ozone were observed. For example, a 10% decrease in ozone occurred in 24 hours over a 3 million square kilometer area. Such a rapid decrease is difficult to explain chemically and is likely the result of transport of ozone-poor air into the region.

- Thus, the current picture of the "ozone hole" is one of an exquisite balance of meteorology and chemistry. Specifically, the unusual physical conditions in Antarctica play a key role in the cause of the "ozone hole". Namely, the low temperatures cause ice particles to form. The ice particles do two things. First, their surfaces host reactions that convert chlorine from the non-reactive form to the reactive form. Secondly, as

> they grow, the ice particles remove reactive nitrogen from the Antarctic stratosphere, which is a chemical change that permits the chlorine to stay in the reactive form, rather than convert back to the non-reactive form. Lastly, the persistent and elevated abundances of reactive chlorine monoxide destroy ozone, yielding the key role of man-induced chemistry in the cause of the "ozone hole".

There are _two_ foci to this picture. If there were no manmade chlorine compounds in the Earth's atmosphere, then there would be no "ozone hole" as it has been observed. If there were no unusual physical conditions in Antarctica, then there would be no "ozone hole" as it has been observed. It apparently takes both, which brings us to the questions of implications.

- o If this picture holds up, then the weight of evidence strongly indicates that manmade chlorinated chemicals play a role in the destruction of ozone in the springtime Antarctic stratosphere.

- o Even though the unusual physical conditions in Antarctic seem to be a necessary condition for the occurrence of the "ozone hole" with the magnitudes observed, _is it possible that a vestige of those conditions could occur elsewhere on the planet, such that small, but similar, ozone losses could happen_? Such losses would only be tiny in comparison to those in Antarctica, but might be scientists and policymakers. Key questions that the Panel may be able to answer include:

- Are the global ozone data sets (from ground-based, balloon-borne, and satellite networks) consistent?
- What is the best composite observational record of global ozone trends from the 1950's to present?
- Is this record consistent with the theory of ozone variation due to solar, nuclear tests, chlorine emissions, and other trace-gas changes?
- In particular, is there an identifiable chlorine-induced signature in any component of the apparent downward trend in ozone since 1979?
- Clearly, data quality may not permit answers to all of these questions. Indeed, data quality is a major aspect of the review.

o Initial Arctic Ozone Studies: In January and February of 1988, several groups will make initial chemical measurements of ozone and related species in the Arctic. NOAA, NASA, universities, Canadians, and Europeans have planned separate, small-scale studies that should be a useful preliminary probe of the contrasts (or similarities) of the Antarctic and Arctic chemistry. The U.S. investigators include those who have previously explored the Antarctic "ozone hole". All of these efforts could comparable to, and hence might significantly add to, the "non-particle" ozone losses predicted to occur elsewhere.

- Lastly, if changing climatic conditions in the southern hemisphere were to be responsible in part for the relatively rapid onset of the "ozone hole" over these last several years, is it possible that climate change elsewhere could make the occurrence of such ozone losses, even to a very small degree, more likely elsewhere on the planet?

These are difficult, but extremely important, policy and scientific questions that cannot be answered satisfactorily at present, but indeed pose valid research goals for the future.

SPECIFIC PROSPECTS FOR INCREASED UNDERSTANDING

With the ratification of the Montreal Protocol being a discussion topic in 1988 and the policy review of the Protocol scheduled for 1990, it is fair to ask what prospects exist for improved scientific understanding (and hence better input to policy) over the next few years. A few specific possibilities can be noted here:

The Short Term: 1988

- Ozone Trends Report: In early 1988, the Ozone Trends Panel will complete its review of existing data. The conclusion regarding the nature of global ozone trends are, for obvious reasons, awaited widely by both be quite useful in providing a first-order look at the scene and provide crucial data for planning possible future experiments.

- Global Ozone Insight: The 1987 Airborne Antarctic Ozone Campaign may be able to provide some insight into the global aspects of ozone-loss processes. Many of the apparatus that operated over Antarctica were also taking data on the "ferry" flight from California to Chile at the beginning of the campaign. During the Antarctic campaign, the emphasis understandably was on analyzing the Antarctic data, but the investigators now have the time to focus on the more-global data gathered on the "ferry" flight.

- International Antarctic Ozone Symposium: In May 1988, there will be an international symposium on Antarctic ozone, sponsored by U.S. agencies, industry, and international science organizations. This open scientific meeting will invite papers on all aspects of Antarctic ozone research. The results, for example, from the 1987 ground-based and airborne campaigns will be ready for publication and presentation. Therefore, on this time scale, the picture of the cause the "ozone hole" should be much more distinct. It is possible that meaningful hypotheses as to its global significance can be presented and debated at this forum.

The Longer Term: 1989-1990

- Ozone Trends: As noted above, global column ozone has both increased and decreased over the 25-year record of observations. Ozone is currently in a declining phase. This decrease, which began in 1979, is the sharpest change on record, and global ozone is lower now than it has been in 25 years. The contributions to this decline have not been separated experimentally, e.g., less ozone generated during the downward phase of the solar cycle or chlorine-induced chlorine depletion. Since the solar cycle is now beginning its upturn, the next few years of trends could provide crucial insight to the degree that this contribution effects global ozone variations. For example, a strong increasing trend for global ozone may point to a dominant current influence of this factor in the cause of ozone variations. It is possible that this insight could be gained in time for the 1989 science assessment that precedes the 1990 policy review of the Montreal Protocol.

EPILOGUE

In concluding, Mr. Chairman, let me make a few general remarks regarding what the ozone issue may have taught us all.

- Scientific discoveries continue to be made and are the product of sustained efforts by inquisitive people (e.g., the "ozone hole"); rather than on-off efforts that are responding, not searching. NOAA has always believed that the long view is its mission and plans to continue that posture.

- Regular assessments of the state-of-the knowledge is a key part of policy refinement, particularly when the scientific assessment is carefully and deliberately couched in terms that are the most useful to policy decisions. For example, the 1985 assessment of the understanding of stratospheric ozone ("Stratospheric Ozone, 1985"; World Meteorological Organization, 1095 pages, 1985) was clearly a crucial basis for the subsequent discussions leading to the Montreal Protocol. NOAA helped translate those science conclusions into a framework more useful for policy makers and pledges to work to continue to improve that process.

- NOAA views the Montreal Protocol as a very important step forward in the ozone/chlorine science/policy issue. It is both a specific start and a malleable document, which are two points that deserve focused attention by all in the coming year. The Montreal Protocol is unprecedented in one subtle, yet crucial, aspect. It appears to be the first time that the nations of the world have joined forces to address an environmental threat in advance of fully established effects. I find this profoundly significant and see it as a watershed. Initial action has been taken on the strength of a theory and its prediction that, because of the time lag between surface emissions and the maximum stratospheric chlorine concentrations, the consequences of current human actions lie in the next century. As such, this placed new requirements on the interplay of science and policy and on the balancing of global economic interests during the debate on this CFC/ozone protocol.

Mr. Chairman, this concluded my prepared remarks. I value the opportunity to submit them. I will be pleased to answer any questions that you and Members of the Subcommittees may have in the future.

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